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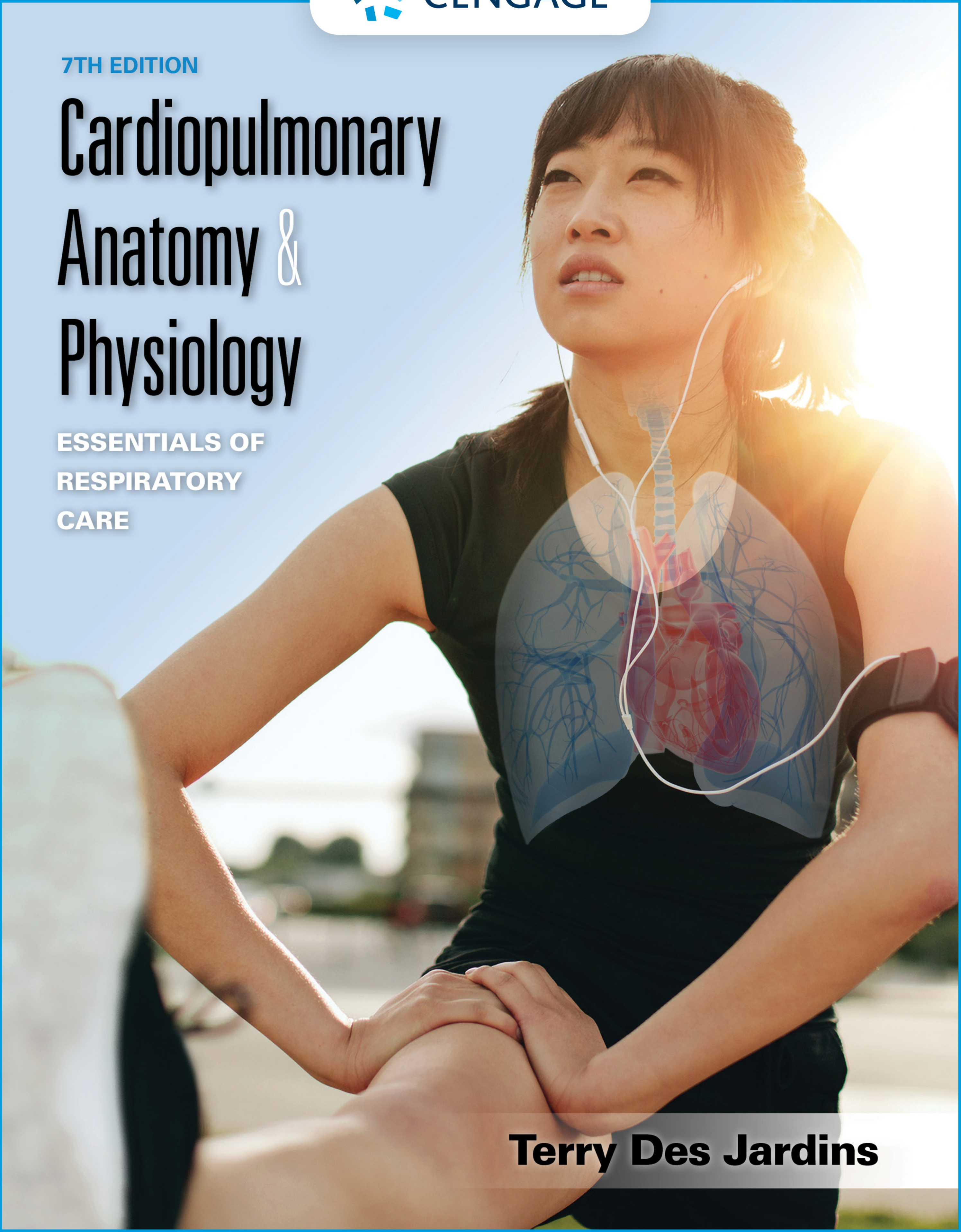

7TH EDITION

Cardiopulmonary Anatomy & Physiology

ESSENTIALS OF RESPIRATORY CARE

Terry Des Jardins

Cardiopulmonary Anatomy & Physiology

ESSENTIALS OF RESPIRATORY CARE

Seventh Edition

To
Katherine, Alexander, Destinee, Ashley, and Jax
The Next Generation
Grandpa T

Cardiopulmonary Anatomy & Physiology

ESSENTIALS OF RESPIRATORY CARE

Seventh Edition

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Cardiopulmonary Anatomy & Physiology – Essentials of Respiratory Care
Seventh Edition
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Foreword

As an educator, it is so delightful to use a book that the students love. This is the case with Terry Des Jardins' *Cardiopulmonary Anatomy & Physiology—Essentials of Respiratory Care*. The new 7th edition expands upon the well proven qualities that make it so "student friendly." First and foremost, this is far more than a standard anatomy and physiology textbook. Students don't complain, "Why do I have to learn this? Is this important?" Terry has tied the essentials of "A&P" to the students' exciting new experiences with patient care. He does this by cross-connecting normal A&P to common pathological conditions that affect the body and real patient situations. For example, in Chapter 1, the discussion of the oral cavity and laryngeal structures is augmented by discussing croup syndrome and endotracheal intubation. Terry brings the normal, the abnormal, and the patient application together in this example and throughout the book.

The text is clearly written and succinctly explains complex topics. Students easily understand what is described to them. Full color art and color photographs further guide the students' visualization of the topic. When appropriate, chest and other radiographs and other medical images are added. As the saying goes, "A picture is worth a thousand words."

Since the anatomy and physiology course typically precedes the pathology course, the Clinical Connections and Clinical Application Cases offer insight into patient care situations. When the pathology course instructor is presenting a disease or condition, croup syndrome for example, it is easy to refer the students back to their earlier learning from this book. The reinforcement of past learning to the present discussion to the future application with a real patient will help guide the students to be knowledgeable and prepared respiratory therapists. A solid understanding of cardiopulmonary anatomy and physiology is the foundation upon which safe, effective patient care is built. Terry's excellent book does just that.

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Preface

Overview

It is important to emphasize that knowledge of an anatomic *structure* is essential to the understanding of the *function* of that structure. It therefore makes little sense to present students with physiologic details without first establishing a solid foundation in anatomy. Because most college-level anatomy courses spend only a limited amount of time on the cardiopulmonary system, respiratory therapy educators generally need to cover this subject themselves. In addition, with regard to a good textbook, respiratory educators usually find the cardiopulmonary section of the college-level anatomy and physiology texts too introductory in nature for the future respiratory therapist's needs.

As a solution to this problem, this book is designed to provide students of cardiopulmonary anatomy and physiology with the most accurate and complete information essential for respiratory care. It is assumed that the student has no previous knowledge of respiratory anatomy or physiology. Great efforts have been made to present a comprehensive overview of the subject matter in an organized, interesting, and readable manner. The organization of this book is based on my experiences as an educator of respiratory anatomy and physiology since 1973—and the countless things I have learned from my students and fellow colleagues. In response to these personal experiences and helpful suggestions, the following pedagogic approach is used in this book.

Organization

The seventh edition of this book is divided into three major sections. **Section 1, *The Cardiopulmonary System—The Essentials,*** consists of Chapters 1 through 11. **Chapter 1** provides the student with a thorough discussion of anatomic structures associated with the respiratory system. This chapter also features a large number of colorful illustrations. The visual impact of this chapter is intended to (1) stimulate interest in the subject under discussion, (2) facilitate the rapid visualization of anatomic structures, and (3) help the student relate classroom knowledge to clinical experiences.

Chapters 2 through 9 cover the major concepts and mechanisms of respiratory physiology. The discussions are comprehensive, logically organized, and, most importantly, presented at a level suitable for the average college student. When appropriate, anatomic and physiologic principles are applied to common clinical situations to enhance understanding and retention (e.g., the gas transport calculations and their clinical application to the patient's hemodynamic status). In addition, a large number of colorful line drawings and tables appear throughout these chapters to assist in the understanding of various concepts and principles.

Chapters 2, 3, 6, 7, and 8 feature several unique line drawings that relate familiar visual concepts to standard graphs and nomograms. While I have found that the types of graphs and nomograms presented in this book are often (at first) difficult for students to understand, it is important to stress that the "physiology literature" uses these items extensively. **The student must understand how to read every graph and nomogram in this book to comprehend its contents fully!**

Chapter 10 covers the major anatomic structures and physiologic mechanisms associated with fetal and newborn gas exchange and circulation. It presents the basic cardiopulmonary foundation required to understand fetal and neonatal respiratory disorders. **Chapter 11** describes changes that occur in the cardiopulmonary system with age. Because the older age groups are expected to increase each year until about the year 2050, basic knowledge of this material will become increasingly important to respiratory care practitioners.

Section 2, ***Advanced Cardiopulmonary Concepts and Related Areas—The Essentials,*** consists of **Chapters 12 through 17. Chapter 12** covers the essential electrophysiology of the heart required for ECG interpretation, **Chapter 13** presents the major components of the standard 12-ECG lead system, and **Chapter 14** provides a systematic approach to ECG interpretation and the major cardiac dysrhythmias seen by the respiratory care practitioner. **Chapter 15** gives the reader the essential knowledge foundation required for hemodynamic measurements and interpretations.

Chapter 16 presents the structure and function of the renal system and the major cardiopulmonary problems that develop when the renal system fails. This chapter is particularly important for respiratory therapist working with patients in the critical care unit. **Chapter 17** presents sleep physiology and its relationship to the cardiopulmonary system. During the past few years, there has been a tremendous increase in the demand for sleep medicine care services. Many of these sleep care centers are staffed with respiratory therapists who work routinely with patients who have various sleep-related disorders that adversely impact the cardiopulmonary system, such as obstructive sleep apnea.

Section 3, ***The Cardiopulmonary System during Unusual Environmental Conditions,*** consists of Chapters 18, 19, and 20. **Chapter 18** presents the effects of exercise on the cardiopulmonary system. During heavy exercise, the components of the cardiopulmonary system may be stressed to their limits. Cardiac patients involved in exercise training after myocardial infarction demonstrate a significant reduction in mortality and major cardiac mishaps. As our older population increases, cardiovascular rehabilitation programs will become increasingly more important to respiratory care practitioners.

Chapter 19 describes the effects of high altitude on the cardiopulmonary system. It provides a better understanding of chronic oxygen deprivation, which can then be applied to the treatment of chronic hypoxia caused by lung disease.

Chapter 20 provides an overview of high-pressure environments and their profound effect on the cardiopulmonary system. The therapeutic administration of oxygen at increased ambient pressures (hyperbaric medicine) is commonly used to treat a number of pathologic conditions.

Finally, at the end of each chapter there is a set of review questions designed to facilitate learning and retention. In addition, at the end of Chapters 2 through 10 and 15, 16, and 17, the reader is provided with a clinical application section. In this part of the chapters, one or two clinical scenarios are presented that apply several of the concepts, principles, or formulas that are presented in the chapter to actual clinical situations. These clinical scenarios are flagged throughout the chapters—in the form of abbreviated Clinical Connections (see description of Clinical Connections below)—to help highlight important points or concepts as they appear in the chapter. This feature further facilitates the transfer of classroom material to the clinical setting. Following the clinical applications are related questions to facilitate the development of critical thinking skills.

A **glossary** is included at the end of the text that further defines many of the key terms that are bolded throughout the textbook. Not all the bolded key terms in the textbook appear in the glossary. This is because, oftentimes, certain terms and phrases are bolded in the text to emphasize certain anatomic structures, concepts, and relationships to enhance the readability of the text.

The glossary is followed by **appendices** that cover symbols, abbreviations, and units of measurement commonly used in respiratory physiology. Also included is a nomogram that can be copied and laminated for use as a handy clinical reference tool in the interpretation of specific arterial blood gas abnormalities. Finally, the **answers** to the chapter review questions appear in the last appendix.

Clinical Connections

Over 140 **Clinical Connections** are interspersed throughout each chapter. The Clinical Connections provide the reader with a direct link between the topics being discussed and, importantly, how they may be applied to the clinical setting and to everyday "real-life" situations. In addition to enhancing the transfer of classroom material to the clinical setting, the Clinical Connections are designed to (1) further stimulate classroom discussions; (2) provide a brief preview (i.e., coming attractions) of more advanced cardiopulmonary topics—such as respiratory disorders, pharmacology, and the benefits and hazards or mechanical ventilation; (3) help in clarifying important cardiopulmonary concepts; and (4) further stimulate the student's excitement—and anticipation—of ultimately working and caring for patients in the profession of respiratory care.

The Clinical Connections are also intended to help the student—the early apprentice of respiratory care—answer the following types of commonly asked questions:

- "Why am I learning this material?"
- "When will I ever see this information in the clinical setting?"
- "How will this material ever be used in my 'real life'—when I am working as a licensed respiratory therapist?"

With the addition of the Clinical Connections, these types of questions are appropriately addressed—the student is now provided with commonly seen relationships between what is being studied in the classroom and how this material may be used in clinical setting.

New to the Seventh Edition

- 150 new or re-rendered colored figures have been added to the text—for a total of over 380 illustrations. These colored illustrations further highlight the important features and concepts associated with the content under discussion.
- 13 new Clinical Connections have been added to the text—for a total of 141 Clinical Connections. The Clinical Connections help to provide a direct link between the chapter content and the clinical setting—and, to "real-life," "everyday" situations. In addition, the Clinical Connections further enhance the student's classroom discussions and critical thinking skills.
- Revised and updated chapter content throughout the entire textbook.

MindTap

MindTap is a personalized teaching experience with relevant assignments that guide students to analyze, apply, and improve thinking, allowing you to measure skills and outcomes with ease.

- Personalized Teaching: Becomes yours with a Learning Path that is built with key student objectives. Control what students see and when they see it. Use it as-is or match to your syllabus exactly–hide, rearrange, add and create your own content.
- Guide Students: A unique learning path of relevant readings and activities that move students up the learning taxonomy from basic knowledge and comprehension to analysis and application.
- Promote Better Outcomes: Empower instructors and motivate students with analytics and reports that provide a snapshot of class progress, time in course, engagement and completion rates.

The MindTap for *Cardiopulmonary Anatomy & Physiology, 7e* features a complete integrated course combining additional quizzing and assignments, and application activities along with the enhanced ebook to further facilitate learning.

Instructor Companion Website

Spend Less Time Planning and More Time Teaching!
With Cengage's Instructor Resources to Accompany *Cardiopulmonary Anatomy & Physiology*, preparing for class and evaluating students has never been easier! As an instructor, you will find this tool offers invaluable assistance by giving you access to all of your resources—anywhere and at any time.

Features:

- Each chapter in the **Instructor's Manual** provides (1) an overview of the content of the chapter; (2) instructional objectives; (3) key terms; (4) instructor and student resources; and (5) a chapter lesson plan and overview—which includes each instructional objective, where in the textbook it is discussed, and what PowerPoint® slides can be used to facilitate the presentation and discussion of the material.
- The **Computerized Testbank** in **Cognero®** makes generating tests and quizzes a snap. With over 1000 questions and different styles to choose from, including multiple choice, true/false, and short answer, you can create customized assessments for your students with the click of a button. Add your own unique questions and print answers for easy class preparation. All questions have been thoroughly updated to reflect content updates made to the seventh edition. Questions have also been edited to provide more correlation to the NBRC exam format.
- Customizable instructor support slide presentations in **PowerPoint®** format focus on key points for each chapter and have been fully updated to correlate to the content updates made to the seventh edition.

Acknowledgments

Several people have provided important contributions to the development of the seventh edition of this textbook. First, a very special thank you goes out to Gayle Carr for the many hours she spent for the research, development, and final edits of the of 13 new Clinical Connections that appear throughout the book. In addition, Gayle provided many important edits and updates throughout the entire textbook. For his outstanding input and wine expertise regarding the clinical connection that discusses the inert gases used to preserve partially filled bottles of wine, a special thank you goes out to Rich Blazier. For the 63 pieces of new or re-rendered artwork for this textbook, a very big shout-out again goes out to Joe Chovan. Joe's outstanding artistic skills continue to enhance the visualization and understanding of the content presented throughout the textbook. For their work and editorial support for the production of the 7th edition of this text, my gratitude goes out to the following from the Cengage Learning staff: Debbie Bordeaux, Mark Peplowski, Sharib Asrar, and Charu Verma. Great job!

SECTION

1

The Cardiopulmonary System

The Essentials

CHAPTER 1
The Anatomy and Physiology of the Respiratory System

CHAPTER 2
Ventilation

CHAPTER 3
Pulmonary Function Measurements

CHAPTER 4
The Diffusion of Pulmonary Gases

CHAPTER 5
The Anatomy and Physiology of the Circulatory System

CHAPTER 6
Oxygen and Carbon Dioxide Transport

CHAPTER 7
Acid–Base Balance and Regulation

CHAPTER 8
Ventilation-Perfusion Relationships

CHAPTER 9
Control of Ventilation

CHAPTER 10
Fetal Development and the Cardiopulmonary System

CHAPTER 11
Aging and the Cardiopulmonary System

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CHAPTER 1

The Anatomy and Physiology of the Respiratory System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the four major components and the primary functions of the upper airways.
2. Identify the structures and the three primary functions of the nose.
3. Identify the structures and function of the upper airways and pharynx.
4. Describe the structure and function of the larynx.
5. Discuss the structure and function of the tracheobronchial tree.
6. Identify the location (generation) and structure of the cartilaginous and noncartilaginous airways.
7. Describe the structure and function of the bronchial blood supply.
8. Describe the sites of gas exchange including the structure and function.
9. Describe the structure and function of the pulmonary vascular system.
10. Discuss the structure and function of the lymphatic system.
11. Identify the effects of sympathetic and parasympathetic nervous systems have on the following: heart, bronchial smooth muscle, bronchial glands, salivary glands, stomach, intestines, and eyes.
12. Identify the structures of the lungs and lung segments from the anterior, posterior, lateral, and medial views.
13. Identify the components of the mediastinum.
14. Identify the components of the pleural membranes.
15. Identify the components of the bony thorax.
16. Describe the structure and function of the diaphragm.
17. Describe the structure and function of the accessory muscles of expiration and inspiration.

The Airways

The passageways between the ambient environment and the gas exchange units of the lungs (the alveoli) are called the **conducting airways**. Although no gas exchange occurs in the conducting airways, they are, nevertheless, important to the overall process of ventilation. The conducting airways are divided into the **upper airways** and the **lower airways**.

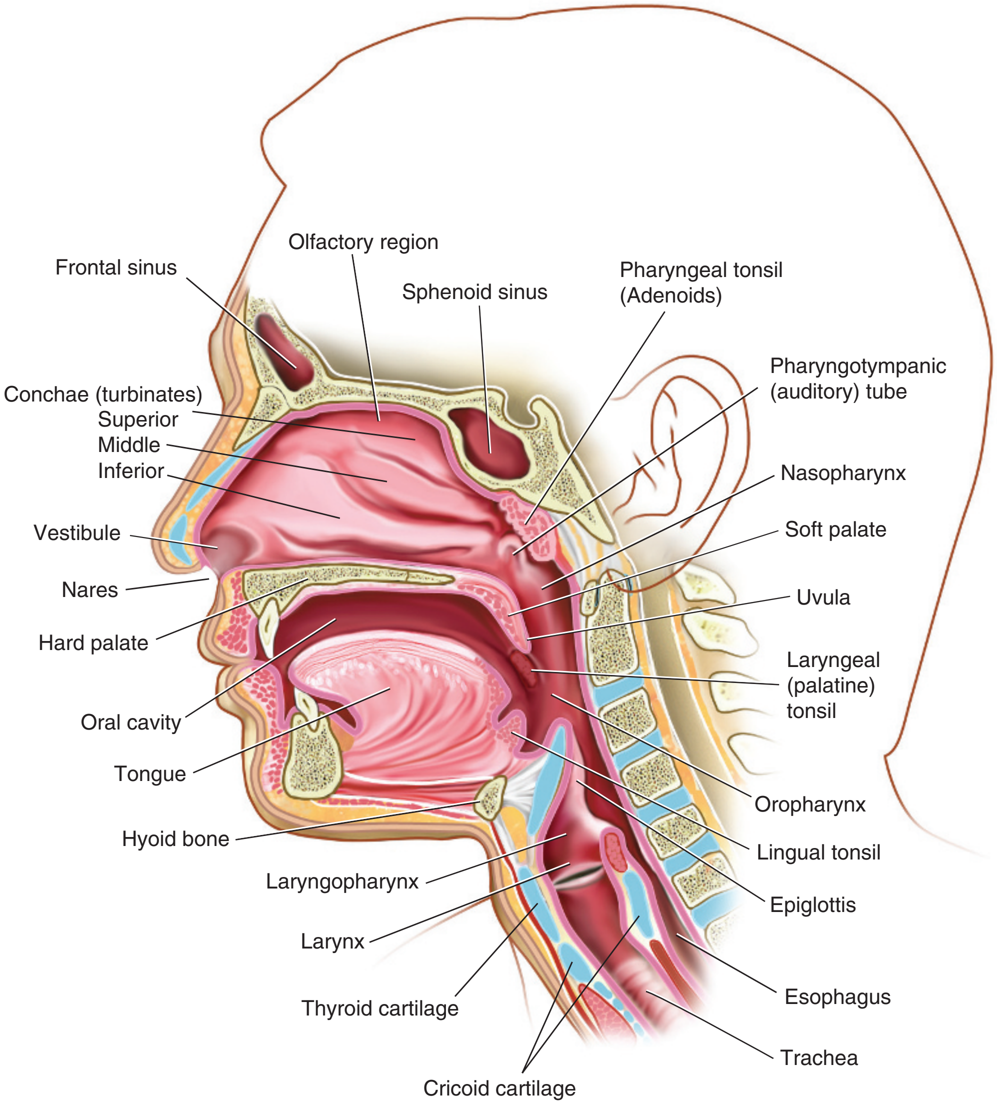
The Upper Airways

The upper airways consist of the **nose**, **oral cavity**, **pharynx**, and **larynx** (Figure 1–1). The primary functions of the upper airways are to (1) act as a conductor of air, (2) humidify and warm or cool the inspired air, (3) prevent foreign materials from entering the tracheobronchial tree, and (4) serve as an important area involved in speech and smell.

The Nose

The primary functions of the nose are to *filter, humidify,* and *condition (warm or cool)* inspired air. The nose is also important as the site for the sense of smell and to generate resonance in phonation.

FIGURE 1–1 Sagittal section of human head, showing the upper airways.


Frontal sinus
Olfactory region
Sphenoid sinus
Pharyngeal tonsil (Adenoids)
Conchae (turbinates)
Superior
Middle
Inferior
Pharyngotympanic (auditory) tube
Nasopharynx
Vestibule
Soft palate
Nares
Uvula
Hard palate
Laryngeal (palatine) tonsil
Oral cavity
Tongue
Oropharynx
Hyoid bone
Lingual tonsil
Laryngopharynx
Epiglottis
Larynx
Esophagus
Thyroid cartilage
Trachea
Cricoid cartilage

The outer portion of the nose is composed of bone and cartilage. The upper third of the nose (the bridge) is formed by the **nasal bones** and the **frontal process** of the **maxilla**. The lower two-thirds consist of the **lateral nasal cartilage**, the **greater alar cartilage**, the **lesser alar cartilages**, the **septal cartilage**, and some **fibrous fatty tissue** (Figure 1–2).

In the internal portion of the nose, a partition, the **nasal septum**, separates the nasal cavity into two approximately equal chambers. Posteriorly, the nasal septum is formed by the **perpendicular plate** of the **ethmoid bone** and by the **vomer**. Anteriorly, the septum is formed by the **septal cartilage**. The roof of the nasal cavity is formed by the **nasal bones**, the **frontal process of the maxilla**, and the **cribriform plate of the ethmoid bone**. The floor is formed by the **palatine process of the maxilla** and by the **palatine bones**—the same bones that form the hard palate of the roof of the mouth. The posterior section of the nasal cavity floor is formed by the superior portion of the **soft palate** of the oral cavity, which consists of a flexible mass of densely packed collagen fibers (Figure 1–3).

Air enters the nasal cavity through the two openings formed by the septal cartilage and the alae nasi, called the **nares**, or **nostrils**. Initially, the air passes through a slightly dilated area called the **vestibule** (see Figure 1–1), which contains hair follicles called **vibrissae**. The vibrissae function as a filter and are the tracheobronchial tree's first line of defense. **Stratified squamous epithelium** (nonciliated) lines the anterior one-third of the nasal cavity (Figure 1–6A). The posterior two-thirds of the nasal cavity are lined with **pseudostratified ciliated columnar epithelium** (Figure 1–6B). The cilia propel mucous toward the nasopharynx.

FIGURE 1–2 Structure of the nose.

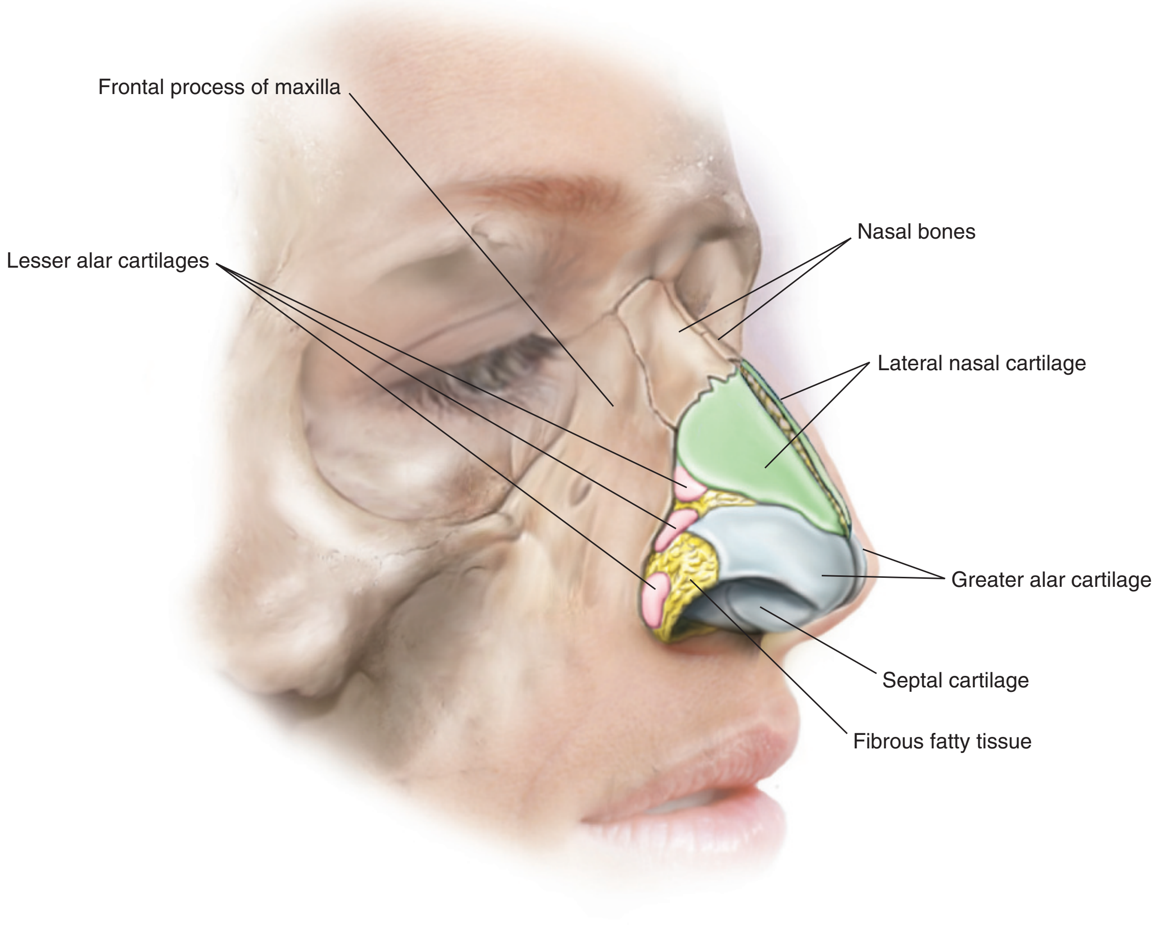
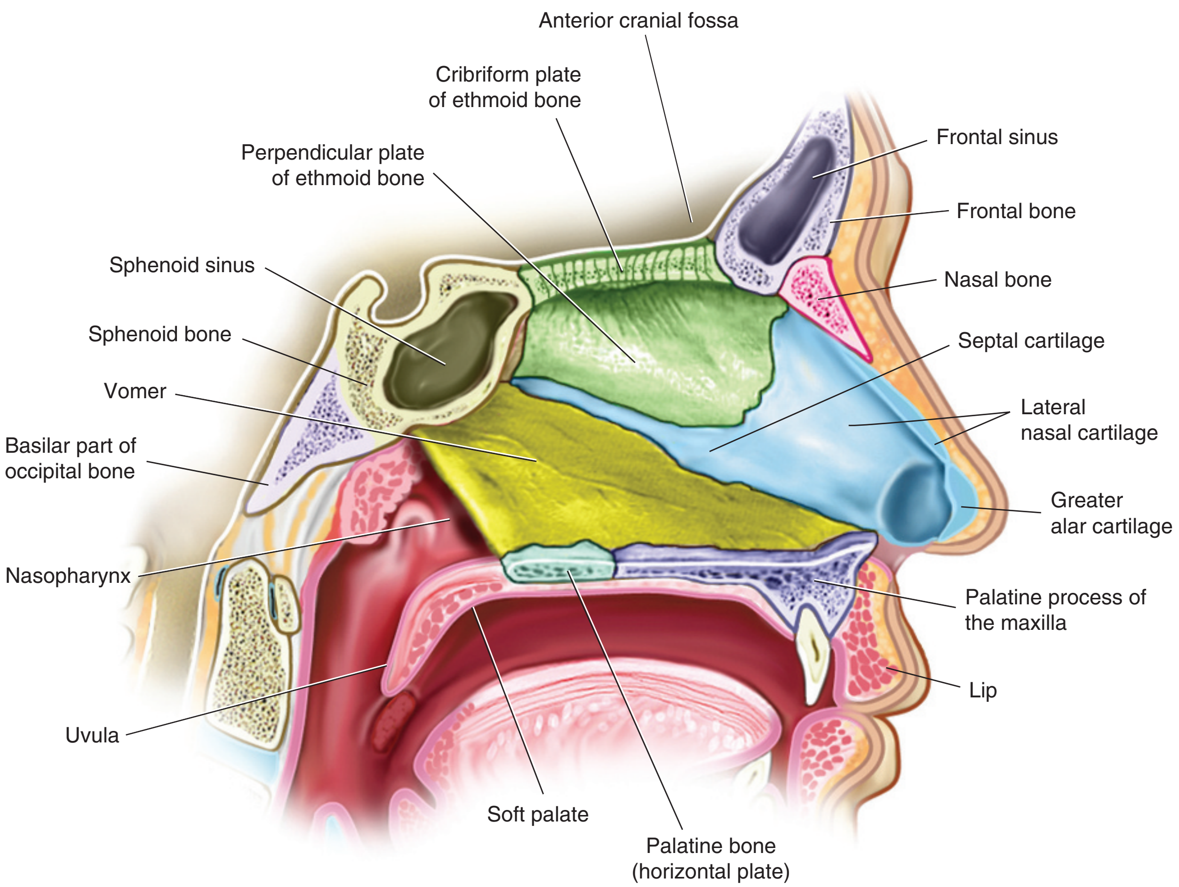


FIGURE 1-3 Sagittal section through the nose, showing the parts of the nasal septum.


Anterior cranial fossa
Cribriform plate of ethmoid bone
Perpendicular plate of ethmoid bone
Frontal sinus
Frontal bone
Nasal bone
Sphenoid sinus
Sphenoid bone
Septal cartilage
Vomer
Lateral nasal cartilage
Basilar part of occipital bone
Greater alar cartilage
Nasopharynx
Palatine process of the maxilla
Lip
Uvula
Soft palate
Palatine bone (horizontal plate)

Clinical Connection 1-1

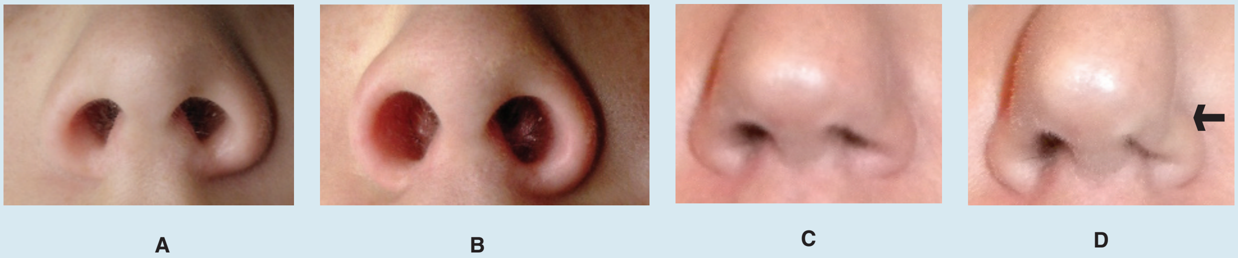
Nasal Flaring and Alar Collapse

Nasal flaring is the widening of the nostrils during periods of respiratory difficulty. The identification of nasal flaring is considered a classic sign of respiratory discomfort—especially in the newborn infant. During periods of respiratory distress—caused by (1) increased airways resistance (e.g., asthma) or (2) lungs that are stiffer than normal (e.g., pneumonia)—the patient commonly generates a greater than normal negative pressure during each inspiration to pull air into the airways more rapidly. The widening of the nostrils further augments the movement of gas flow into the nasal passage during each inspiration (Figure 1–4A and B). Common respiratory disorders associated with nasal flaring include respiratory distress syndrome of the newborn infant, pneumonia, acute asthma, and any airways obstruction. Clinically, aggressive respiratory therapy modalities should be activated to increase the patient's arterial blood oxygen level.

The reverse of nasal flaring is called **alar collapse** and is an important sign of nasal obstruction (Figure 1–4C and D). Nasal obstruction causes the victim to be an obligate mouth breather, and it is one of the causes of snoring and obstructive sleep apnea (refer to Chapter 17).

Clinical Connection 1-1, Continued

FIGURE 1-4 **A.** Normal nostrils. **B.** Nasal flaring. **C.** Patient with alar collapse during exhalation. **D.** Patient with alar collapse during inspiration.

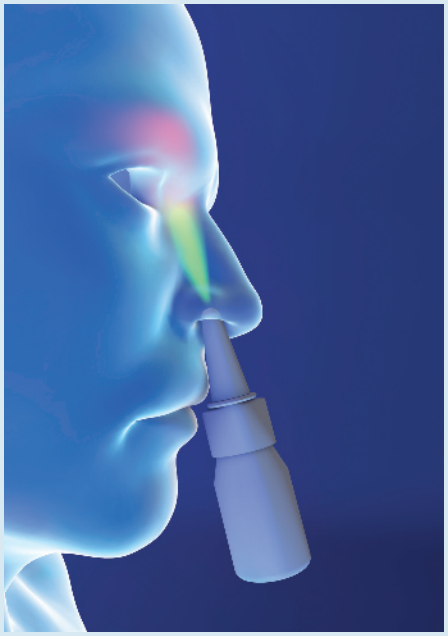


Courtesy T. Des Jardins, WindMist LLC

Clinical Connection 1-2

The Nose—A Route of Administration for Topical Agents

FIGURE 1-5 Nasal spray.



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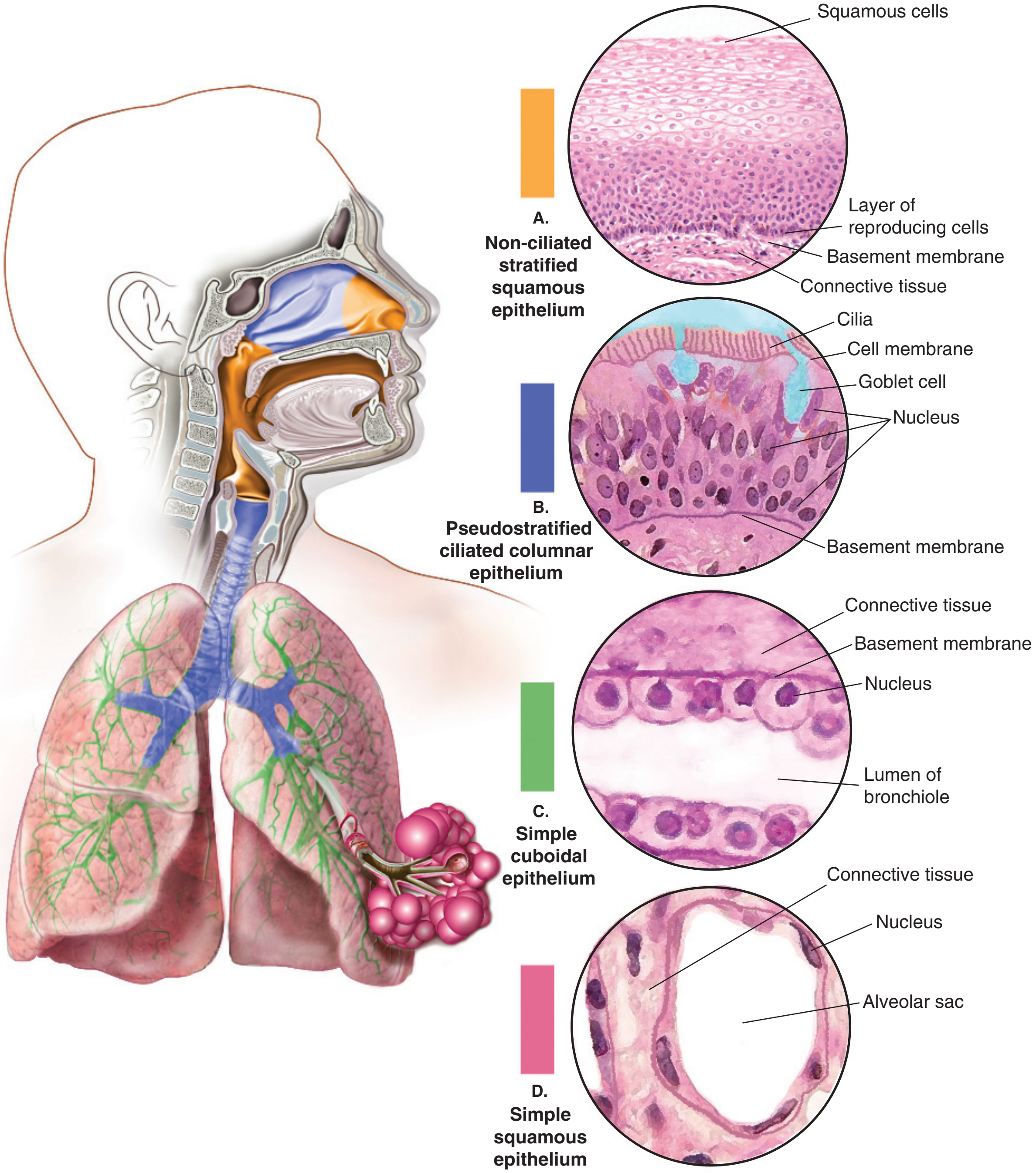
Because of the large quantity of blood vessels located near the surface of the nasal mucosa, the nose serves as an excellent route of administration for a variety of topical drugs in the form of nasal sprays or nasal drops (Figure 1–5). Such drugs can be applied directly to the mucous membranes to produce a local effect, with little or no systemic absorption. For example, in cold remedies, medications such as Neo-Synephrine® (phenylephrine) are commonly applied for their sympathomimetic, alpha-stimulating, and vasoconstriction effects to treat nasal congestion. Abuse of this class of drugs is, unfortunately, common. Overuse of topical nasal decongestants can result in the undesired effect of engorgement of the nasal membranes.

Synthetic corticosteroids—such as budesonide—are used to treat nasal mucosa inflammation. Ipratropium bromide, an anticholinergic agent, is used to treat nasal congestion, sneezing, and itchy, runny nose. In addition, other medications, including influenza vaccines, can be delivered by intranasal administration.

There are three bony protrusions on the lateral walls of the nasal cavity called the **superior**, **middle**, and **inferior nasal turbinates**, or **conchae** (see Figure 1–1). The turbinates separate inspired gas into several different airstreams—this action increases the contact area between the inspired air and the warm, moist surface of the nasal mucosa. The nasal mucosa has a rich supply of blood vessels and nerve endings. When the inspired air is cold, the vascular system becomes engorged with blood and warms the air. The turbinates

FIGURE 1-6 Epithelium of the conducting airways. **A. Stratified squamous epithelium** consists of several layers of cells. This tissue is found in the anterior portion of the nasal cavity, oral cavity, oropharynx, and laryngopharynx. **B. Pseudostratified ciliated columnar epithelium** appears stratified because the nuclei of the cells are located at different levels. These cells have microscopic hairlike projections called cilia that extend from the outer surface. Mucous-producing goblet cells are also found throughout this tissue. Pseudostratified columnar ciliated epithelium lines the posterior two-thirds of the nasal cavity and the tracheobronchial tree. **C. Simple cuboidal epithelium** consists of a single layer of cube-shaped cells. These cells are found in the bronchioles. **D. Simple squamous epithelium** consists of a single layer of thin, flattened cells with broad and thin nuclei. Substances such as oxygen and carbon dioxide readily pass through this type of tissue. These cells form the walls of the alveoli and the pulmonary capillaries that surround the alveoli.


Squamous cells
A.
Non-ciliated stratified squamous epithelium
Layer of reproducing cells
Basement membrane
Connective tissue
Cilia
Cell membrane
Goblet cell
Nucleus
B.
Pseudostratified ciliated columnar epithelium
Basement membrane
Connective tissue
Basement membrane
Nucleus
C.
Simple cuboidal epithelium
Lumen of bronchiole
Connective tissue
Nucleus
Alveolar sac
D.
Simple squamous epithelium

play a major role in the humidification and warming of inspired air. The receptors for the sense of smell are located in the **olfactory region**, which is near the superior and middle turbinates. When the nasal mucosa nerve endings are irritated with particles—such as powder, dust, or pollen—a sneeze reflex is triggered. The two nasal passageways between the nares and the nasopharynx are also called the **choanae**.

Clinical Connection 1-3

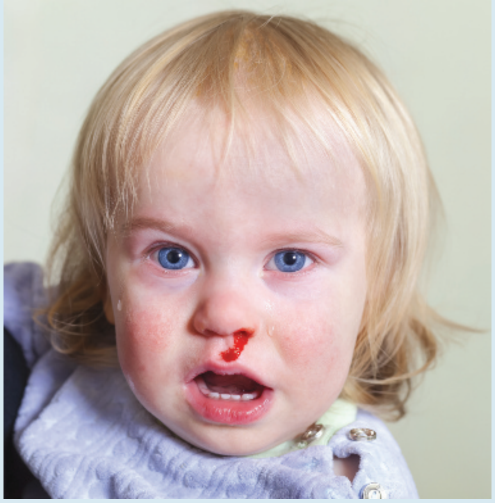
Nosebleeds (Epistaxis)

Because of the abundance and superficial location of the vascular system throughout the mucosa of the nasal cavity—especially the anterior septum area—nosebleeds are commonly seen both in and out of the hospital setting (Figure 1–7). The nosebleed may be profuse or merely a minor complication. Nosebleeds tend to occur more often during the winter months, when the air is dry and warmed by household heaters. Nosebleeds can also occur in a hot and dry climate with low humidity. In other words, nosebleeds tend to occur during periods of low humidity. Although nosebleeds may occur at any age, they are most commonly seen in children between 2 and 10 years of age and in adults between 50 and 80 years of age.

Nosebleeds are classified as either *anterior,* originating from the highly vascularized anterior septum of the nose, or *posterior,* originating from the back of the nose. **Anterior nosebleeds** make up more than 90 percent of nosebleeds and are usually stopped at home by simply pinching the nostrils closed or packing them with cotton. **Posterior nosebleeds** are much less common. The bleeding usually originates from an artery located in the back of the nasal cavity. Blood usually flows down the back of the pharynx—even when the person is sitting or standing. Posterior nosebleeds tend to occur more often in the elderly and are usually more complicated. Posterior nosebleeds can be very serious and may require hospitalization for management.

Common causes of anterior nosebleeds include trauma (e.g., a hard blow or smack to the nose), nose-picking and trauma from foreign bodies (common in children), a difficult nasal intubation, exposure to cold and dry climates with low humidity, exposure to a hot and dry climate with low humidity, high altitudes, head colds and allergies, and certain medications. For example, individuals are more susceptible to nosebleeds when they are taking the anti-blood-clotting medication warfarin (Coumadin® or Panwarfarin®), aspirin, or any anti-inflammatory medications. Significant nosebleeds can result in these cases.

FIGURE 1-7 Nosebleed.



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When the nosebleed is caused by dry nasal mucosa, a little water-soluble jelly, applied about 0.5 inch into the nose using a Q-tip, two to four times a day, may be helpful. Although a room humidifier may be helpful, caution must be taken to prevent the growth of molds and other allergens. Do not use a petroleum-based product (e.g., Vaseline). A petroleum-based product will dry, not moisten, the nose. In the hospital setting, the respiratory therapist adds humidity to oxygen therapy when flow rates exceed 4 liters per minute.

Common causes of posterior nosebleeds include serious nose trauma (e.g., displaced broken nose from a motor vehicle accident or fall), nasal mucosal infections, high blood pressure, nasal tumors, atherosclerosis, drug abuse (e.g., cocaine), and leukemia. Treatment includes packing the nose with cotton or inserting an inflatable balloon to stop the bleeding. Cauterization of the ruptured blood vessels may be required.

Clinical Connection 1-4

Nasal Congestion and Its Influence on Taste

Taste can be profoundly affected by nasal congestion (Figure 1–8).

An individual's taste is strongly influenced by olfactory sensations. It is estimated that more than 80 percent of our taste sensation depends on the sense of smell. When the olfactory receptors in the nasal cavity are blocked by nasal congestion, the taste of food is bland. Without the sense of smell, our morning coffee would lack its richness and taste bitter. Bacon, eggs, and hot cinnamon rolls would taste bland. This is why individuals with a head cold often complain that they cannot taste their food. This phenomenon can easily be experienced by pinching one's nose to close off the nasal passages, while trying to taste a particular type of food.

FIGURE 1–8 Nasal congestion.

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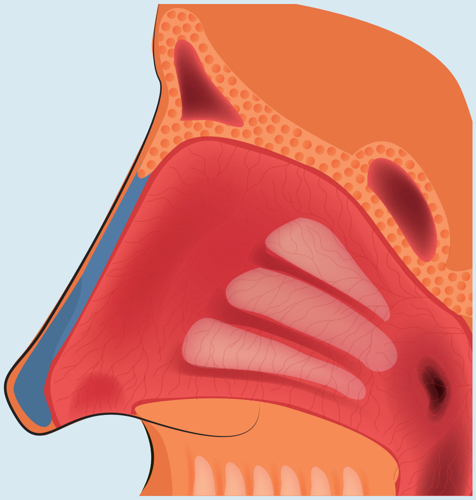
Clinical Connection 1-5

Rhinitis

Rhinitis is the inflammation of the mucous membranes of the nasal cavity and is usually accompanied by swelling of the mucosa, excessive mucous production, nasal congestion, and postnasal drip (Figure 1–9). Cold viruses, streptococcal bacteria, and various allergens commonly cause rhinitis. Because the nasal mucosa extends into the nasolacrimal (tear) ducts and the passageways leading to the paranasal sinuses, a nasal cavity infection often spreads to these areas—resulting in sinusitis (see Clinical Connection 1–6: Sinusitis). When the passageways connecting the paranasal sinuses to the nasal cavity are blocked by mucous or infection—without any sinus involvement—the air in the sinus cavities is absorbed; this, in turn, results in a partial vacuum and a sinus headache.

FIGURE 1–9 Rhinitis.



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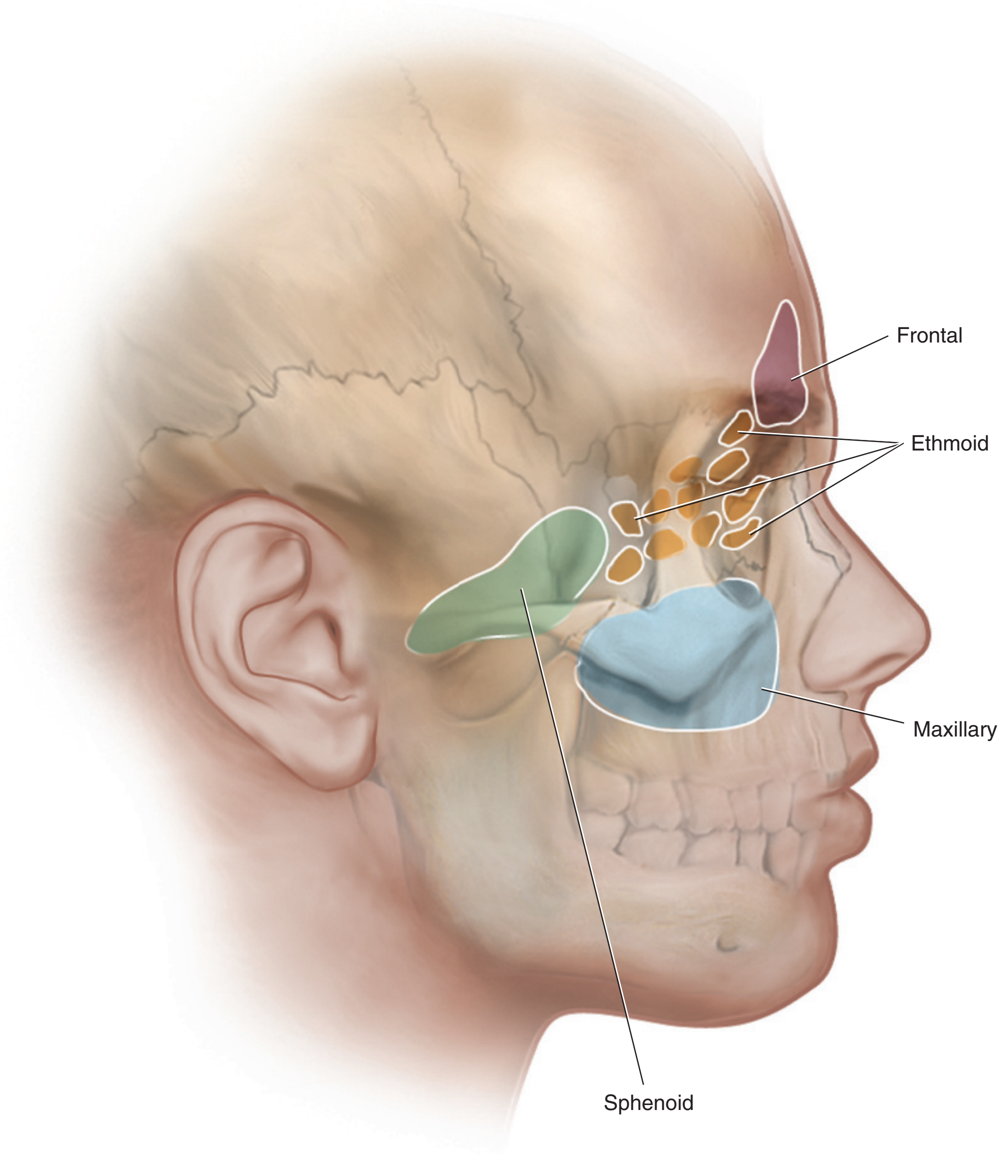
Immediately below the superior and middle turbinates are the openings of the paranasal sinuses, which are air-filled cavities in the bones of the skull that communicate with the nasal cavity. The paranasal sinuses include the **maxillary**, **frontal**, **ethmoid**, and **sphenoid sinuses** (Figure 1–10). The paranasal sinuses produce mucous for the nasal cavity and act as resonating chambers for the production of sound.

Oral Cavity

The **oral cavity** is considered an accessory respiratory passage. It consists of the **vestibule**, which is the small outer portion between the teeth (and gums) and lips, and a larger section behind the teeth and gums

FIGURE 1-10 Lateral view of the head, showing sinuses.

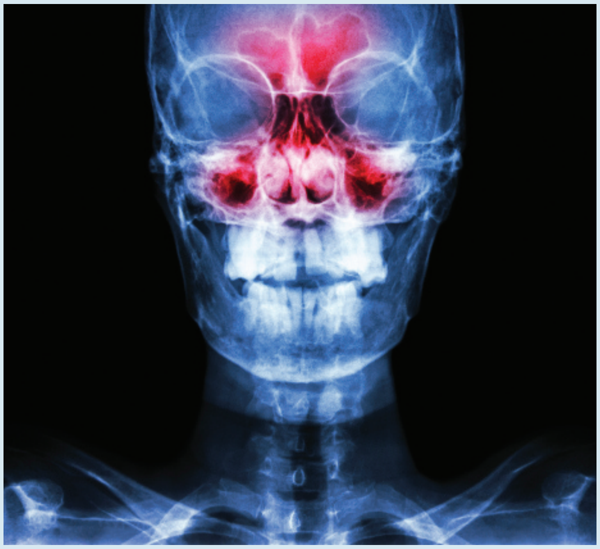


Clinical Connection 1-6

Sinusitis

An inflammation of the mucous membrane of one or more of the paranasal sinuses is called **sinusitis** (Figure 1–11). Sinusitis can be caused by an upper respiratory infection, dental infection, atmospheric pressure changes (e.g., air travel or underwater swimming), placement of a nasal endotracheal tube, or a structural defect of the nasal cavity. When the mucous membranes become inflamed, they swell and produce excess mucous. As the swelling and mucous production intensifies, the passageways leading to the nasal cavity become partially or completely obstructed, resulting in sinus secretion accumulation. The mucous accumulation within the paranasal sinuses further promotes the development of bacterial infections. The mucous accumulation causes pressure, pain, headaches, fever, and local tenderness. Treatment consists of antibiotics to treat bacterial infections and various therapeutic modalities designed to enhance sinus drainage, such as decongestants, hydration, and steam inhalation.

FIGURE 1-11 Sinusitis. Anterior-posterior X-ray film showing infection and inflammation at frontal sinus, ethmoid sinus, maxillary sinus.



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Clinical Connection 1-7

Nasal Polyps

Nasal polyps (NP) are noncancerous overgrowths of mucous membranes that appear in the nose and sinuses (Figure 1–12). The growths are sac-like and moveable and usually are not painful. They typically develop in both nostrils. The precise cause is not known but may be related to chronic inflammation of the lining of nose and sinuses. NP occur more frequently among people with allergies, cystic fibrosis, and aspirin sensitivity. Symptoms include nasal congestion, sinusitis, trouble breathing through the nose, runny nose, postnasal drip, nasal speech, mouth breathing, and loss of smell and decreased taste sensation. The diagnosis is made by looking up the nose. Treatment includes steroid nasal sprays, and surgery may be considered.

FIGURE 1-12 Nasal polyps.

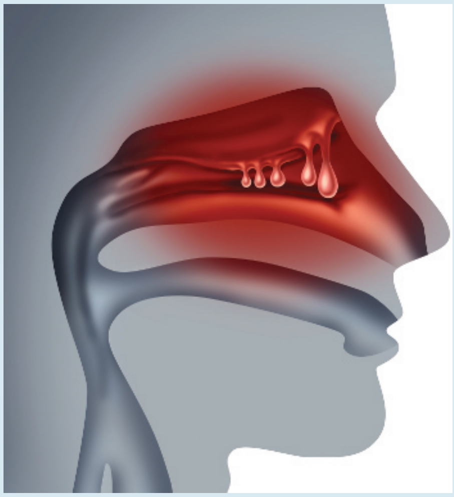

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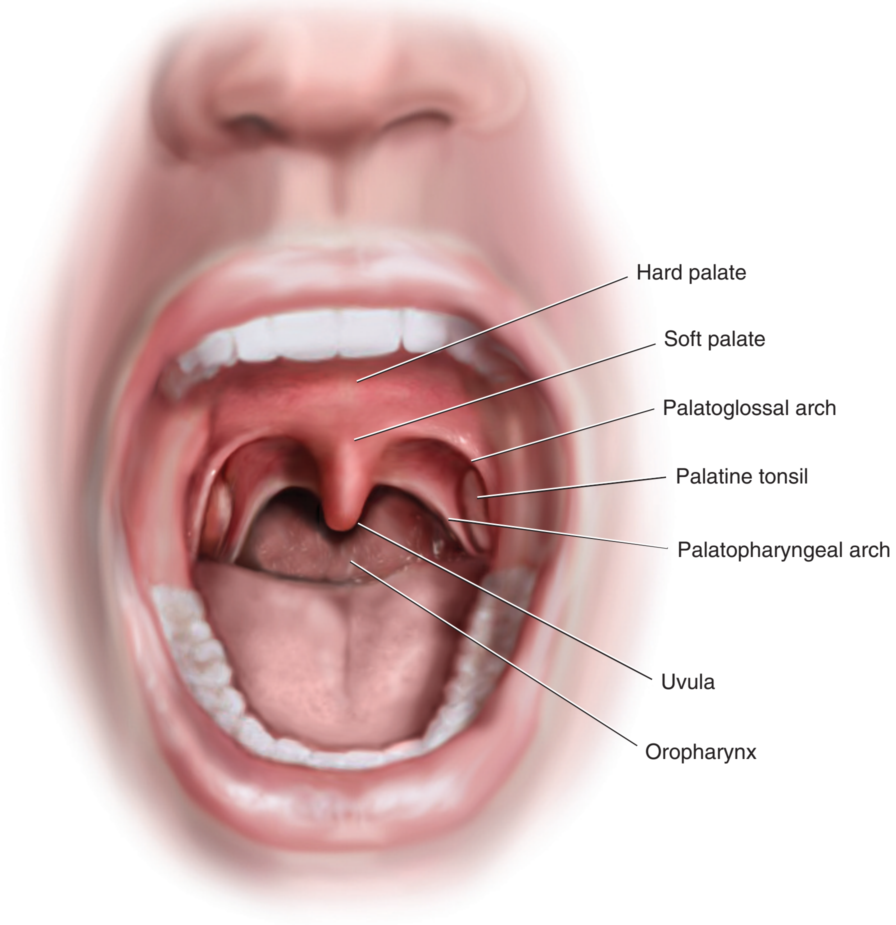
FIGURE 1-13 Oral cavity.



that extends back to the oropharynx (Figure 1–13). The **tongue** is located on the floor of the oral cavity and fills most of the oral cavity when the mouth is closed. The tongue is composed of interlacing bundles of skeletal muscles and fibers. When chewing food, the tongue holds the food and continuously repositions it between the teeth. In addition, the tongue mixes the food with saliva and forms a compact mass called a **bolus**, and then initiates swallowing by moving the bolus posteriorly into the pharynx. During speech, the tongue is used to help form consonants such as *k, d,* and *t*.

The tongue consists of both intrinsic and extrinsic skeletal muscle fibers. The **intrinsic muscles** are only located in the tongue and are not attached to bone. The intrinsic muscle fibers allow the tongue to change its shape—for example, to become thinner, thicker, longer, or shorter. The intrinsic muscles are also used during speech and swallowing. The extrinsic muscles of the tongue extend from their points of origin on bones of the skull or of the soft palate. The extrinsic muscles allow the tongue to change position—for example, protrude outward, retract inward, or move it from side to side.

The tongue is secured to the floor of the mouth by a fold of mucosa called **lingual frenulum**. The lingual frenulum also limits posterior movements of the tongue. Taste buds are found in papillae, peg-like projections of the tongue mucosa, which give the tongue surface a slightly abrasive feel. The taste buds can be grouped into one of the following basic qualities: sweet, sour, salty, bitter, and umami (a savory taste produced by several amino acids).

The roof of the mouth is formed by the **hard** and **soft palate**. The hard palate is composed of the **palatine process of the maxilla** and the **palatine bones** (see Figure 1–3). The soft palate consists of a flexible mass of densely packed collagen fiber that projects backward and downward, ending in the soft, fleshy structure called the **uvula** (see Figure 1–13). The soft palate closes off the opening between the nasal and oral pharynx by moving upward and backward during swallowing, sucking, and blowing and during the production of certain speech sounds. The **levator veli palatinum muscle** elevates the soft palate, and the **palatopharyngeal muscles** draw the soft palate forward and downward. The oral cavity is lined with nonciliated **stratified squamous epithelium** (see Figure 1–6A).

Two folds of mucous membrane pass along the lateral borders of the posterior portion of the oral cavity. These folds form the **palatoglossal arch** and the **palatopharyngeal arch**, named for the muscles they cover. Collectively, these arches are called the **palatine arches**. The **palatine tonsils** (faucial) are located between the palatine arches on each side of the oral cavity (see Figure 1–13). The palatine tonsils, like the pharyngeal tonsils or nasopharynx adenoids, are lymphoid tissues and are believed to serve certain immunologic defense functions.

The Pharynx

After the inspired air passes through the nasal cavity, it enters the pharynx. The **pharynx** is divided into three parts: nasopharynx, oropharynx, and laryngopharynx (see Figure 1–1).

Nasopharynx

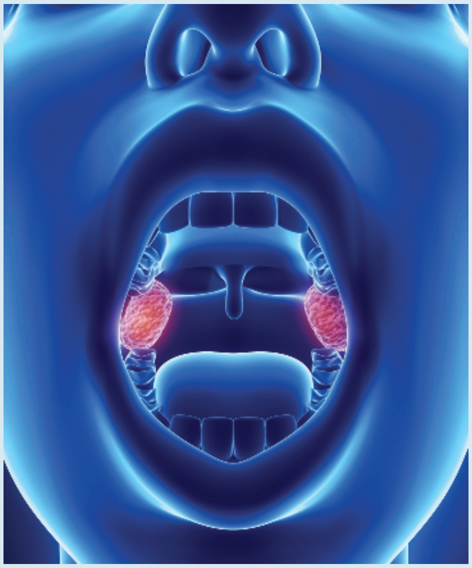
The nasopharynx is located between the posterior portion of the nasal cavity (posterior nares) and the superior portion of the soft palate. The nasopharynx is lined with pseudostratified ciliated columnar epithelium (see Figure 1–6B). The **pharyngeal tonsil** (also called the **adenoid**) is located in the posterior nasopharynx. A tonsil is a large mass of lymphatic nodules and diffuse lymphatic tissue that protect against bacteria and

Clinical Connection 1-8

Infected and Swollen Pharyngeal Tonsils (Adenoids)

When the pharyngeal tonsil is infected and swollen, inspired air through the nose becomes partially or completely blocked—making it necessary to breathe through the mouth (Figure 1–14). As a result, the inspired air is not adequately humidified, warmed, or filtered before entering the lungs. A chronically enlarged pharyngeal tonsil can adversely affect speech and sleep and may require surgical removal.

FIGURE 1-14 Swollen pharyngeal tonsils (adenoids) shown in red.



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other harmful substances that enter the nasopharynx. When the pharyngeal tonsil is inflamed and swollen, it may completely block the passage of air between the nose and throat (see Figure 1–1).

The openings of the **pharyngotympanic (auditory) tubes**, formerly called the *eustachian tubes,* are located on the lateral surface of the nasopharynx. The pharyngotympanic tubes run downward to connect the middle ears to the nasopharynx and serve to equalize the pressure in the middle ear. The mucosa of the middle ear is continuous with the mucosa that lines the pharynx (throat). Normally, the pharyngotympanic tubes are flattened and closed. However, when swallowing or yawning, the tubes open briefly to equalize pressure in the middle ear cavity with internal air pressure. The ear-popping sensation of pressures equalizing is familiar to anyone who has flown in an airplane or traveled through a mountainous terrain. Inflammation and excessive mucous production in the pharyngotympanic tube may disrupt the pressure-equalizing process and impair hearing. This problem is frequently seen in young children with **otitis media** (i.e., ear infection).

Oropharynx

The oropharynx lies between the soft palate superiorly and the base of the tongue inferiorly (at the level of the hyoid bone) (see Figure 1–1). Two groups of tonsils are located in the oropharynx. The **palatine tonsils**—which are usually referred to as "the tonsils"—are relatively large, oval in shape, located on each side of the oral cavity between the palatopharyngeal arch and the palatoglossal arch (see Figure 1–13).

The **lingual tonsil** is a loosely associated collection of lymphatic nodules located on the posterior base of the tongue. The mucosa of the oropharynx is composed of nonciliated stratified squamous epithelium (see Figure 1–6A). The **vallecula epiglottica** is located between the glossoepiglottic folds on each side of the posterior oropharynx. It appears as a depression or crevice that runs from the base of

Clinical Connection 1-9

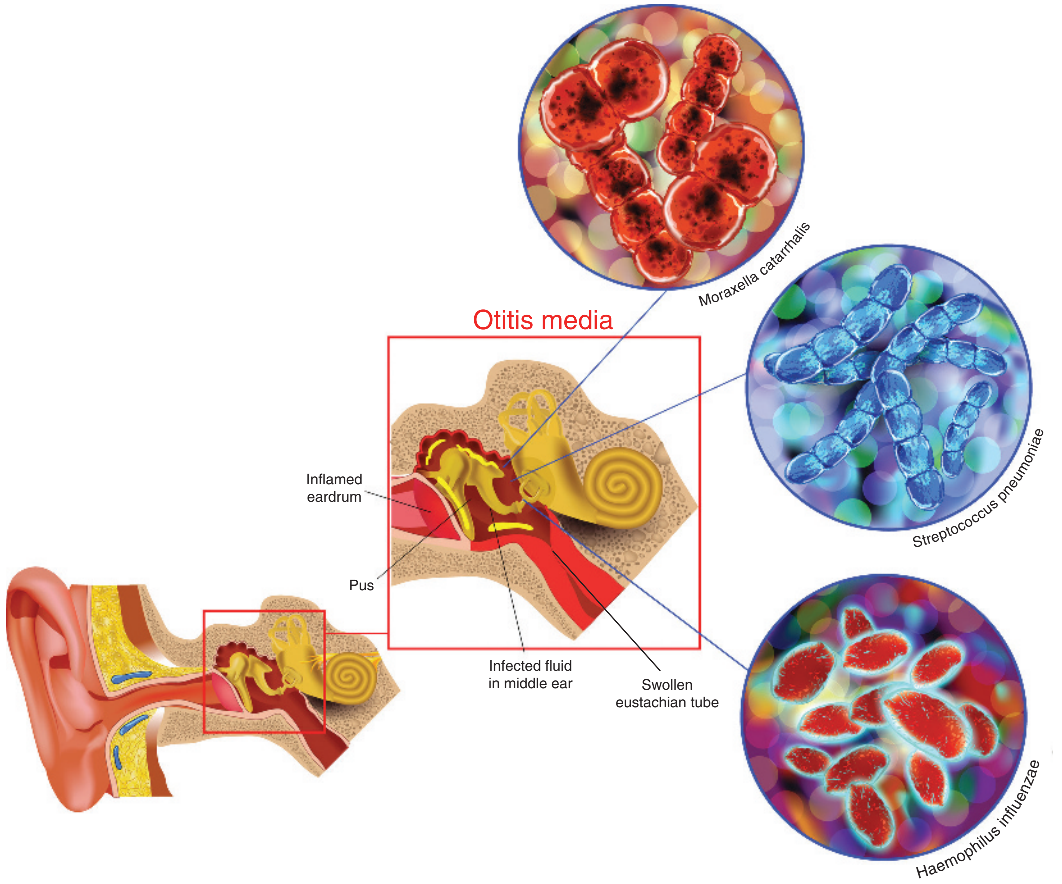
Otitis Media

Otitis media, or **middle ear infection,** is fairly common in young children with a recent history of a sore throat (Figure 1–15). These infections usually develop from an infection of mucous membranes of the pharynx that spreads through the pharyngotympanic (auditory) tubes to the mucous lining of the middle ear. Common causes of otitis media include *Moraxella catarrhalis, Streptococcus pneumoniae*, and *Haemophilus influenzae*. In young children, the pharyngotympanic tubes are shorter and run more horizontally. This is because the head of a young child is usually more round in shape. This round shape of the head causes the pharyngotympanic tubes to be more horizontal—which cannot always drain adequately when they become infected. As the child grows older, the head becomes more oval in shape and the auditory tubes shift downward or become more vertical in the upright position.

The symptoms of otitis media consist of a low-grade fever, lethargy, and irritability—symptoms that are often not easily recognized by a parent as being a middle ear infection. Otitis media is the most frequent cause of hearing loss in young children and is a result of fluid buildup that dampens the tympanic membrane, or eardrum. During an acute middle ear infection, the eardrum bulges and becomes inflamed and red. Most cases of otitis media are treated with antibiotics. When large amounts of fluid or pus accumulate in the middle ear, a *myringotomy* (lancing of the eardrum) may be performed to relieve the pressure. A tiny tube inserted in the eardrum permits drainage into the external ear. The tube usually falls out on its own within a year.

Clinical Connection 1-9, Continued

FIGURE 1-15 Otitis media.



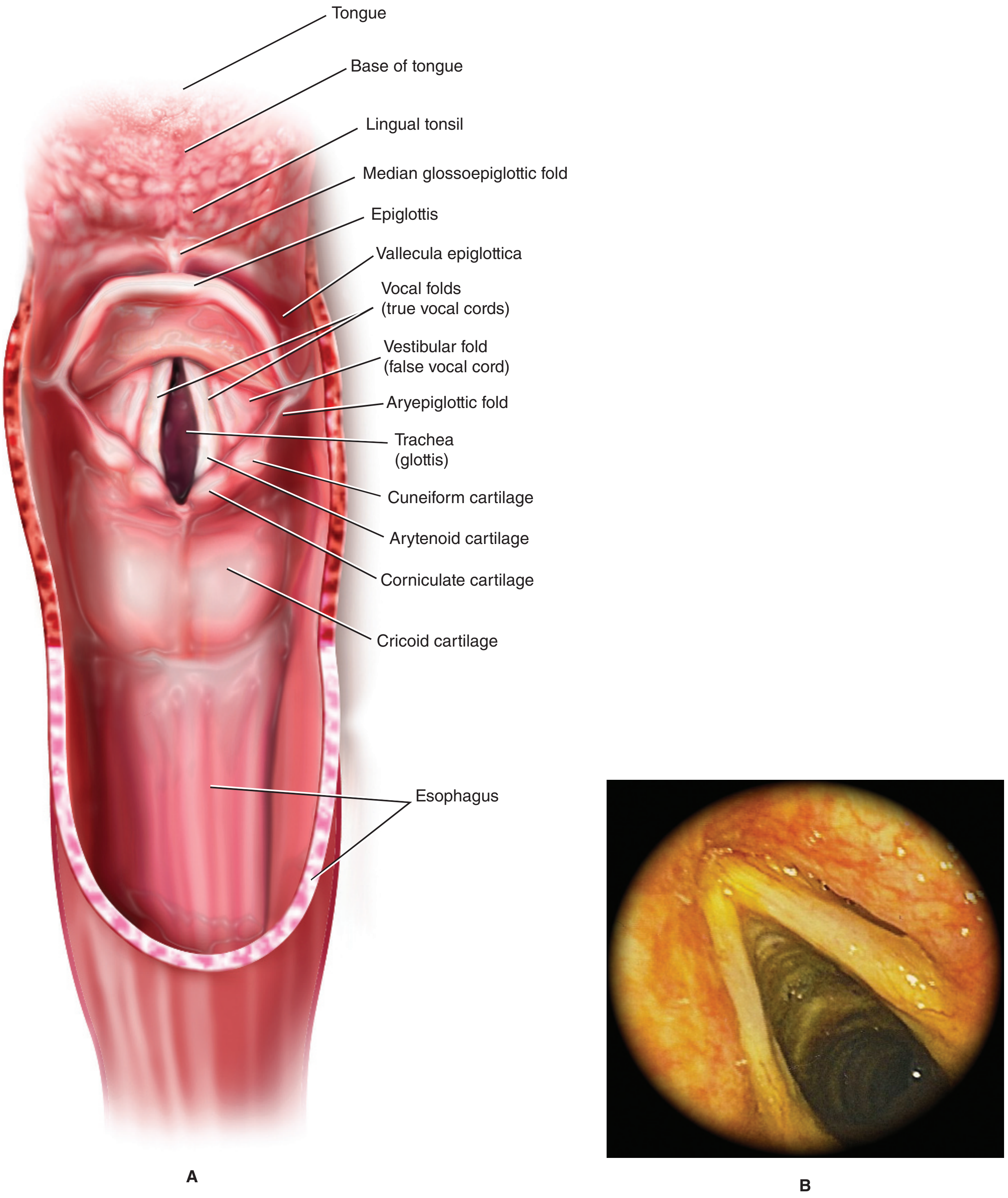
the tongue to the epiglottis (Figure 1–16). The vallecula epiglottica is an important anatomic landmark during the insertion of an endotracheal tube into the trachea (see next section for more information about endotracheal tubes).

Laryngopharynx

The **laryngopharynx** (also called the hypopharynx) lies between the base of the tongue and the entrance of the **esophagus**. The laryngopharynx is lined with nonciliated stratified squamous epithelium (see Figure 1–6A). The epiglottis, the upper part of the larynx, is positioned directly anterior to the laryngopharynx (see Figure 1–1). The **aryepiglottic folds** are mucous membrane folds that extend around the margins of the larynx from the epiglottis. They function as a sphincter during swallowing. Clinically, the major structures associated with the laryngopharynx are often viewed from above using a laryngoscope while the patient is supine—especially note the close proximity of the epiglottis, vocal cords, and esophagus (see Figure 1–16).

The laryngopharyngeal musculature receives its sensory innervation from the ninth cranial (glossopharyngeal) nerve and its motor innervation from the tenth cranial (vagus) nerve. When stimulated, these muscles and nerves work together to produce the **pharyngeal reflex** (also called the "gag" or "swallowing" reflex), which helps to prevent the aspiration of foods and liquids. It also helps to prevent the base of the tongue from falling back and obstructing the laryngopharynx, even in the person who is asleep in the supine position.

FIGURE 1-16 **A.** View of the base of the tongue, vallecula epiglottica, epiglottis, and vocal cords. **B.** Photo of the vocal cords.


Tongue
Base of tongue
Lingual tonsil
Median glossoepiglottic fold
Epiglottis
Vallecula epiglottica
Vocal folds (true vocal cords)
Vestibular fold (false vocal cord)
Aryepiglottic fold
Trachea (glottis)
Cuneiform cartilage
Arytenoid cartilage
Corniculate cartilage
Cricoid cartilage
Esophagus
A
B

Courtesy T. Des Jardins, WindMist LLC

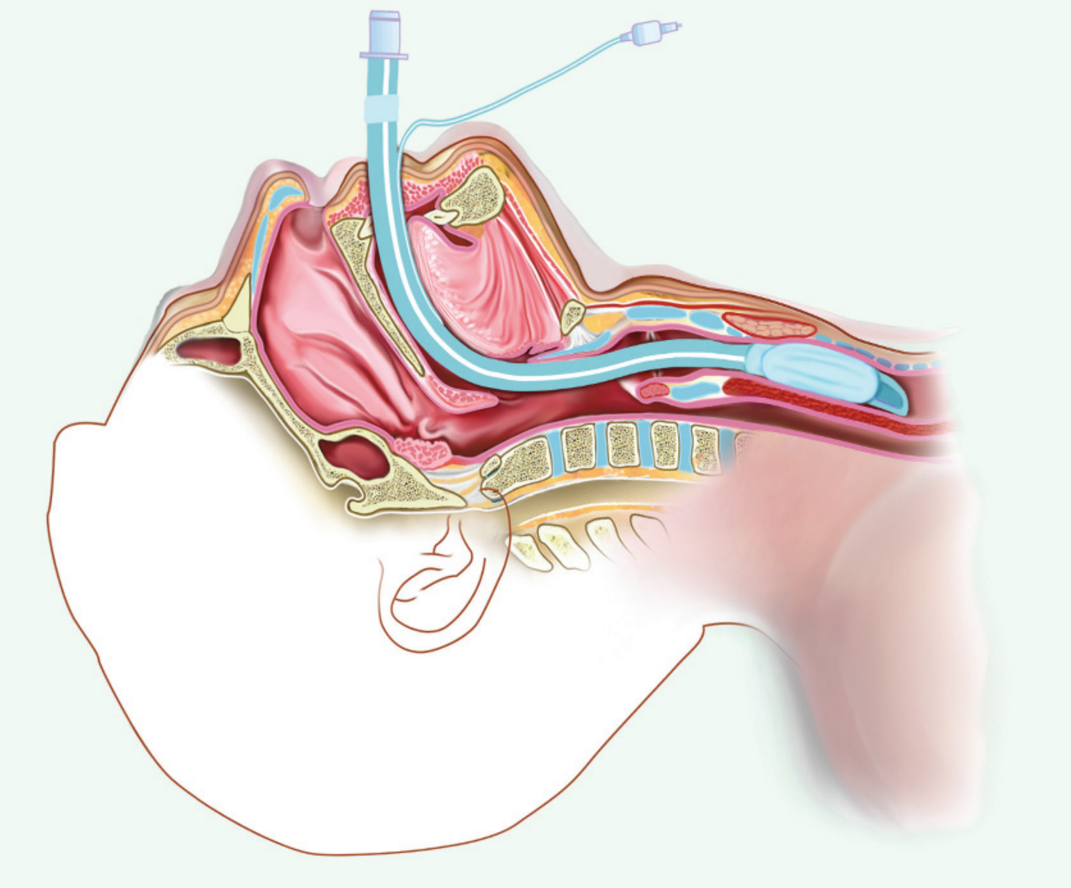
Clinical Connection 1-10

Endotracheal Tubes

In the clinical setting, the respiratory therapist frequently bypasses the entire upper airways to better *ventilate* and *oxygenate* the patient. A **nasal endotracheal tube**, an **oral endotracheal tube**, or a **tracheostomy tube** can be used to bypass the patient's upper airways (Figure 1–17). When an endotracheal tube is in place, the gas being delivered to the patient must be appropriately *warmed* and *humidified*. Failure to do so dehydrates the mucous layer of the tracheobronchial tree, which in turn causes the mucous layer to become thick and immobile and the mucous itself to become thick and sticky.

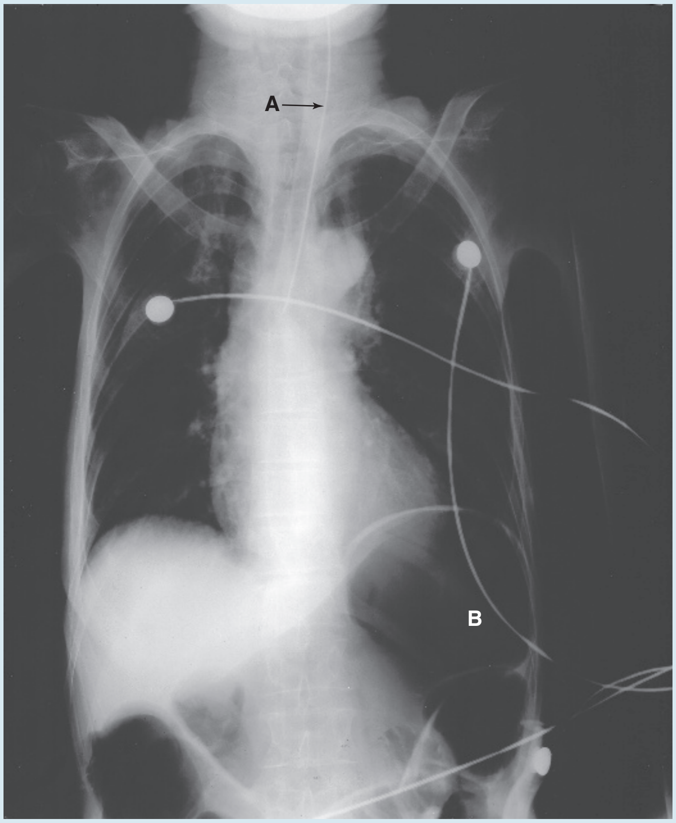
The respiratory therapist must learn—and differentiate—the major anatomic landmarks of the laryngopharynx and larynx (e.g., vallecula, epiglottis, esophagus, vocal folds, and trachea), especially when inserting an endotracheal tube. Moreover, the intubator should always be mindful of the fact that (1) the *glottis* is the smallest part of the airways for the adult, and (2) the *cricoid cartilage* is the smallest portion of the upper airways in the infant and child. In addition, an endotracheal tube can easily be inserted into the patient's esophagus rather than into the trachea, especially during an emergency situation. When this occurs, the patient's stomach—rather than lungs—is ventilated. A misplaced endotracheal tube in the esophagus can be fatal (Figure 1–18).

FIGURE 1-17 An oral endotracheal tube placed in proper position in the trachea. The inflated cuff at the tip of the tube separates the lower airways from the upper airways.



Clinical Connection 1-10, Continued

FIGURE 1-18 **A.** An endotracheal tube misplaced in a patient's esophagus. Note that the endotracheal tube is positioned to the right (patient's left) of the spinal column. Clinically, this is an excellent sign that the tube is in the esophagus. **B.** Stomach inflated with air.



The Larynx

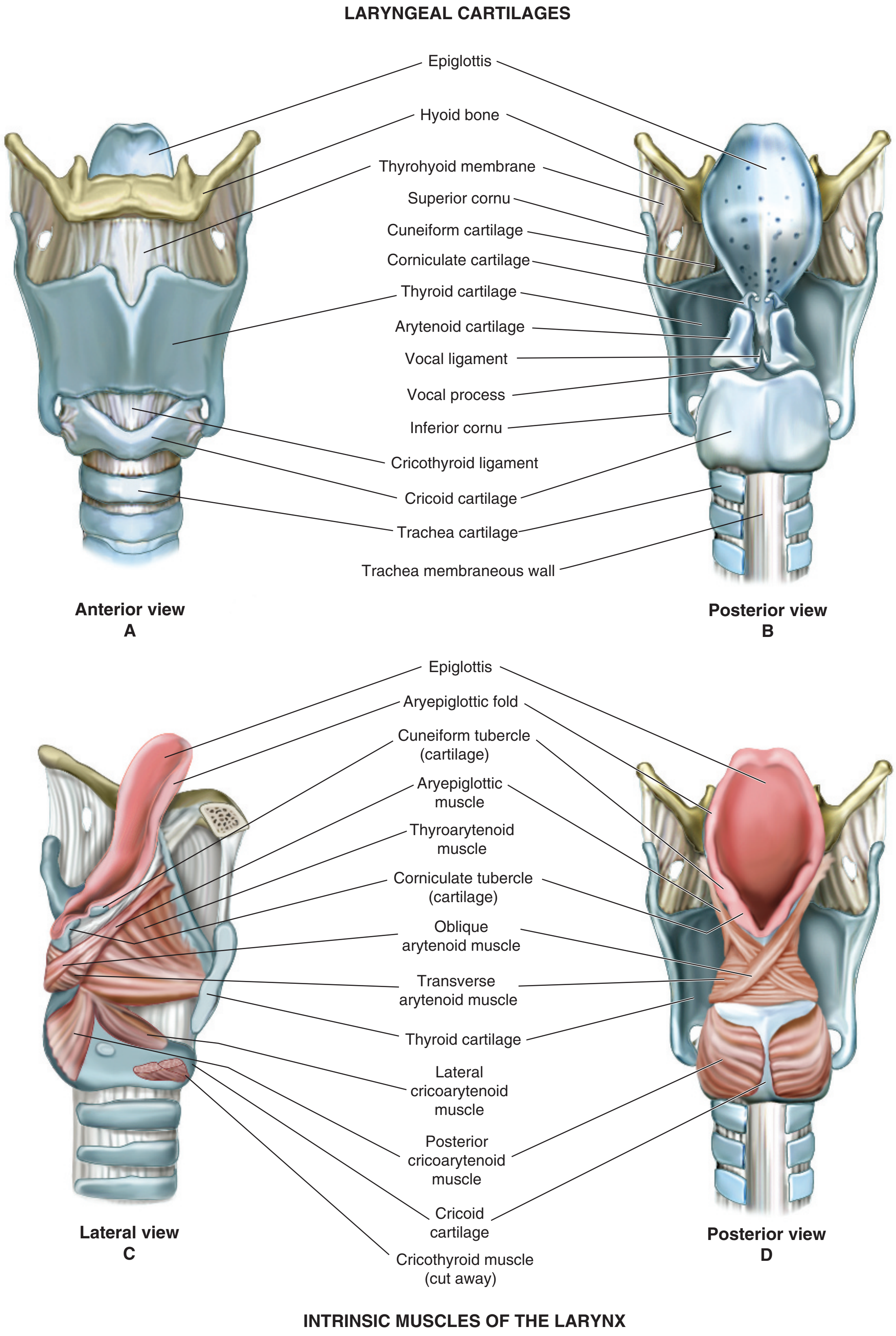
The **larynx**, or voice box, is located between the base of the tongue and the upper end of the trachea (see Figure 1–1). The larynx is commonly described as a vestibule opening into the trachea from the pharynx. The larynx serves three functions: (1) it acts as a passageway of air between the pharynx and the trachea, (2) it serves as a protective mechanism against the aspiration of solids and liquids, and (3) it generates sounds for speech.

Cartilages of the Larynx

The larynx consists of a framework of nine cartilages (Figure 1–19). Three are single cartilages: **thyroid cartilage**, **cricoid cartilage**, and the **epiglottis**. Three are paired cartilages: **arytenoid**, **corniculate**, and **cuneiform cartilages** (see Figure 1–19A and B). The cartilages of the larynx are held in position by ligaments, membranes, and **intrinsic** and **extrinsic muscles**. The interior of the larynx is lined with mucous membrane.

The thyroid cartilage (commonly called the Adam's apple) is the largest cartilage of the larynx. It is a double-winged structure that spreads over the anterior portion of the larynx. Along its superior border is a V-shaped notch, the **thyroid notch**. The upper portion of the thyroid cartilage is suspended from the horseshoe-shaped hyoid bone by the **thyrohyoid membrane**. Technically, the hyoid bone is not a part of the larynx.

FIGURE 1-19 Cartilages and intrinsic muscles of the larynx.


LARYNGEAL CARTILAGES
Epiglottis
Hyoid bone
Thyrohyoid membrane
Superior cornu
Cuneiform cartilage
Corniculate cartilage
Thyroid cartilage
Arytenoid cartilage
Vocal ligament
Vocal process
Inferior cornu
Cricothyroid ligament
Cricoid cartilage
Trachea cartilage
Trachea membraneous wall
Anterior view
A
Posterior view
B
Epiglottis
Aryepiglottic fold
Cuneiform tubercle (cartilage)
Aryepiglottic muscle
Thyroarytenoid muscle
Corniculate tubercle (cartilage)
Oblique arytenoid muscle
Transverse arytenoid muscle
Thyroid cartilage
Lateral cricoarytenoid muscle
Posterior cricoarytenoid muscle
Cricoid cartilage
Cricothyroid muscle (cut away)
Lateral view
C
Posterior view
D
INTRINSIC MUSCLES OF THE LARYNX

The epiglottis is a broad, spoon-shaped fibrocartilaginous structure. Normally, it prevents the aspiration of foods and liquids by covering the opening of the larynx during swallowing. The epiglottis and the base of the tongue are connected by folds of mucous membranes, which form a small space (the vallecula) between the epiglottis and the base of the tongue. Clinically, the vallecula serves as an important anatomic landmark when inserting an endotracheal tube (see Figure 1–16).

The cricoid cartilage is shaped like a signet ring. It is located inferior to the thyroid cartilage and forms a large portion of the posterior wall of the larynx. The inferior border of the cricoid cartilage is attached to the first C-shaped cartilage of the trachea (see Figure 1–19).

The paired arytenoid cartilages are shaped like a three-sided pyramid. The base of each arytenoid cartilage rests on the superior surface of the posterior portion of the cricoid cartilage. The apex of each arytenoid cartilage curves posteriorly and medially and flattens for articulation with the corniculate cartilages. At the base of each arytenoid cartilage is a projection called the **vocal process**. The **vocal ligaments**, which form the medial portion of the vocal folds, attach to the vocal process.

The paired cuneiform cartilages and corniculate cartilages are small accessory cartilages that are closely associated with the arytenoid cartilages. The cuneiform cartilages are embedded within the aryepiglottic folds that extend from the apices of the arytenoid cartilages to the epiglottis. They probably act to stiffen the folds. The two corniculate cartilages lie superior to the arytenoid cartilages.

Interior of the Larynx

The interior portion of the larynx is lined by a mucous membrane that forms two pairs of folds that protrude inward. The upper pair are called the **false vocal folds** because they play no role in vocalization. The lower pair functions as the **true vocal folds** (vocal cords). The medial border of each vocal fold is composed of a strong band of elastic tissue called the **vocal ligament**. Anteriorly, the vocal cords attach to the posterior surface of the thyroid cartilage. Posteriorly, the vocal folds attach to the vocal process of the arytenoid cartilage. The arytenoid cartilages can rotate about a vertical axis through the cricoarytenoid joint, allowing the medial border to move anteriorly or posteriorly. This action, in turn, loosens or tightens the true vocal cords.

The space between the true vocal cords is termed the **rima glottidis** or, for ease of reference, the **glottis** (see Figure 1–16). In the adult, the glottis is the narrowest point in the larynx. In the infant, the cricoid cartilage is the narrowest point. Glottic and subglottic swelling (edema) secondary to viral or bacterial infection is commonly seen in infants and young children and is known as the **croup syndrome**.

Above the vocal cords, the laryngeal mucosa is composed of (nonciliated) stratified squamous epithelium (see Figure 1–6A). Below the vocal cords, the laryngeal mucosa is covered by pseudostratified ciliated columnar epithelium (see Figure 1–6B).

Clinical Connection 1-11

Laryngitis

Laryngitis is an inflammation of the mucous membrane lining the larynx, accompanied by swelling and edema of the vocal cords (Figure 1–20). This condition causes hoarseness or complete loss of voice. Laryngitis can be caused by a number of things, including heavy smoking, bacterial infections, very dry air, inhalation of irritating fumes, sudden temperature changes, overuse of the voice, and tumors. Of particular importance to the respiratory therapist is the laryngitis caused by **post-extubation laryngeal edema**. Because the endotracheal tube is placed between the vocal cords of the larynx for extended periods of time, the vocal cords often have some degree of trauma, edema, and swelling.

In response to acute laryngitis, the patient may have a cough or may complain of a sore, scratchy

(*Continued*)

Clinical Connection 1-11, Continued

throat. In young children, acute laryngitis may cause severe respiratory distress. This is because the relatively small vocal cords of the young child have a tendency to spasm when they become irritated, inflamed, or infected. In these cases, partial or complete airways obstruction can occur. Treatment consists of an aerosolized alpha-adrenergic drug, such as racemic epinephrine—the treatment of choice for post-extubation laryngeal edema—high humidification (vaporized cool mists and steam inhalation), avoidance of any irritants (e.g., smoke, fumes, dust), voice rest, cough medication, and antiseptic throat sprays.

FIGURE 1-20 Laryngitis.

Clinical Connection 1-12

Croup Syndrome

A common clinical manifestation seen in children is **croup** (also called **inspiratory stridor**). The term *croup* is a general term used to describe the inspiratory, barking, or brassy sound associated with a partial upper airways obstruction—in short, a croup sound is a "clinical sign." The two major causes of croup—that is, a barking or brassy inspiratory sound—are **laryngotracheobronchitis** (LTB) and **acute epiglottitis**.

Acute epiglottitis is a supraglottic airways obstruction resulting from inflammation of the epiglottis, aryepiglottic folds, and false vocal folds—**and is a life-threatening emergency**! Acute epiglottis is almost always caused by a bacterial infection of **Haemophilus influenzae type B** (Figure 1–21A). Figure 1–21B shows a lateral X-ray of a 27-year-old man with severe epiglottitis.

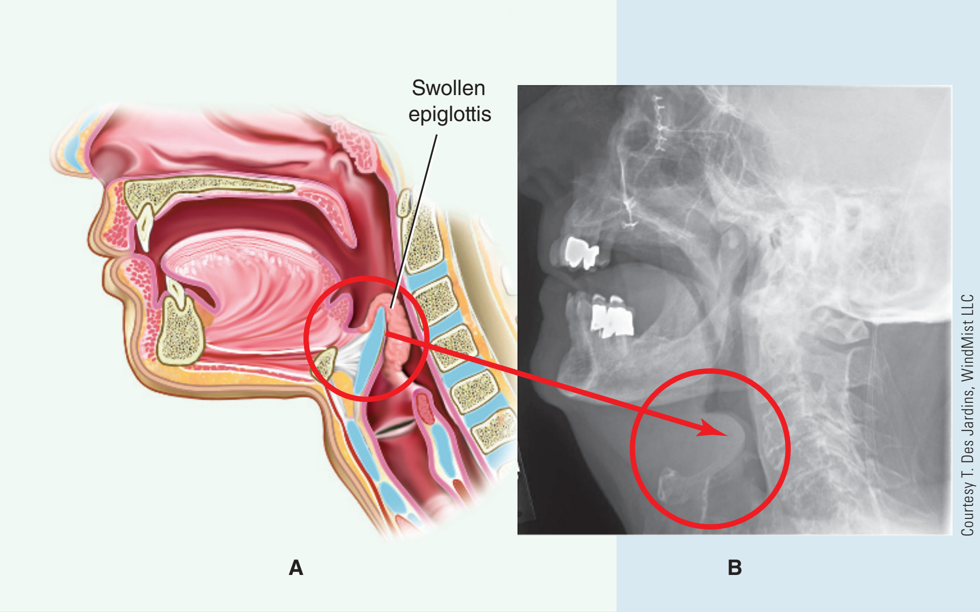
LTB is a subglottic airways obstruction; acute epiglottitis is a supraglottic airways obstruction (see Figure 1–22A). Pathologically, LTB is an inflammatory process that causes edema and swelling of the mucous membranes below the glottis. Figure 1–22B shows a chest X-ray of a 3-year-old patient with a LTB obstruction. The **parainfluenza virus** causes most LTB cases.

Aerosolized **racemic epinephrine** is commonly used to treat LTB for its alpha-adrenergic stimulation—which causes mucosal vascular constriction. This action, in turn, reduces the edema

Clinical Connection 1-12, Continued

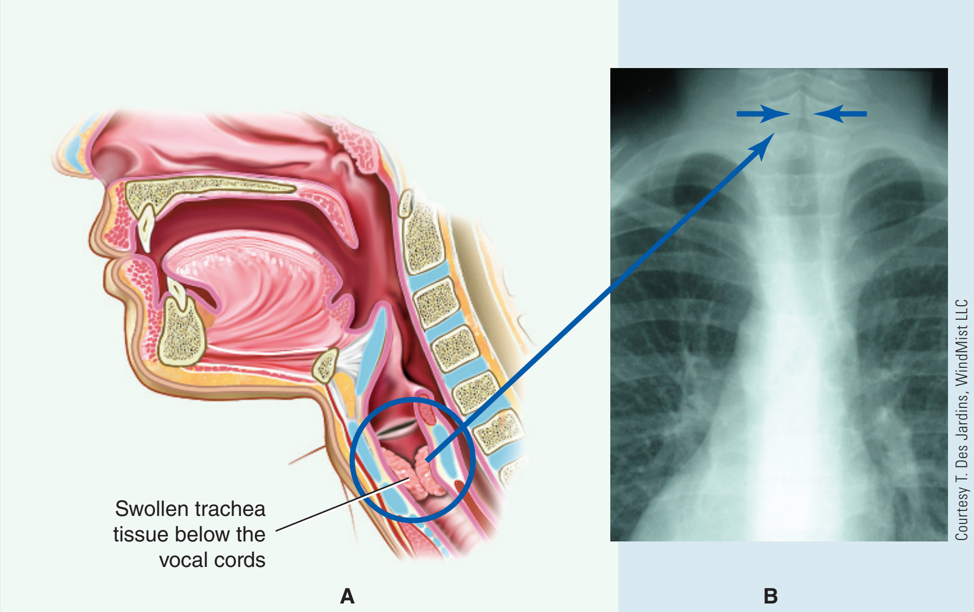
and swelling of the airway—in short, racemic epinephrine widens the subglottic airway. Racemic epinephrine has long been recognized as an effective and safe aerosol decongestant. In patients with a suspected acute epiglottitis, an examination of the pharynx and larynx is absolutely contraindicated, except in the operating room with a fully trained team in attendance.

FIGURE 1-21 **A.** Acute epiglottitis (swollen epiglottis). **B.** A 27-year-old male with severe epiglottis (arrow) caused by crack cocaine abuse and upper neck and head trauma from a motorcycle accident.



Courtesy T. Des Jardins, WindMist LLC

FIGURE 1-22 **A.** LTB, swollen trachea tissue below the vocal cords. **B.** Close-up of neck on a chest X-ray of a 3-year-old patient with a subglottic airways narrowing.



Courtesy T. Des Jardins, WindMist LLC

Laryngeal Musculature

The muscles of the larynx consist of the extrinsic and intrinsic muscle groups. The extrinsic muscles are subdivided into an infrahyoid and a suprahyoid group. The infrahyoid group consists of the sternohyoid, sternothyroid, thyrohyoid, and omohyoid muscles (Figure 1–23). These muscles pull the larynx and hyoid bone down to a lower position in the neck. The suprahyoid group consists of the stylohyoid, mylohyoid, digastric, and geniohyoid muscles. These muscles pull the hyoid bone forward, upward, and backward—which can be seen when a person swallows (see Figure 1–23). The major intrinsic muscles that control the movement of the vocal folds are illustrated in Figure 1–19C and D. The action(s) of these muscles are described next.

Posterior Cricoarytenoid Muscles. These muscles pull inferiorly on the lateral angles of the arytenoids, causing the vocal folds to move apart (abduct) and thus allowing air to pass through (Figure 1–24A).

Lateral Cricoarytenoid Muscles. The action of these muscles opposes that of the posterior cricoarytenoid muscles. These muscles pull laterally on the lateral angles of the arytenoids, causing the vocal folds to move together (adduct) (Figure 1–24B).

Transverse Arytenoid Muscles. These muscles pull the arytenoid cartilages together and thereby position the two vocal folds so that they vibrate as air passes between them during exhalation, thus generating the sounds for speech or singing (Figure 1–24C).

Thyroarytenoid Muscles. These muscles lie in the vocal folds lateral to the vocal ligaments. Contraction of the thyroarytenoid muscles pulls the arytenoid cartilages forward. This action loosens the vocal ligaments and allows a lower frequency of phonation (Figure 1–24D).

FIGURE 1-23 Extrinsic laryngeal muscles.

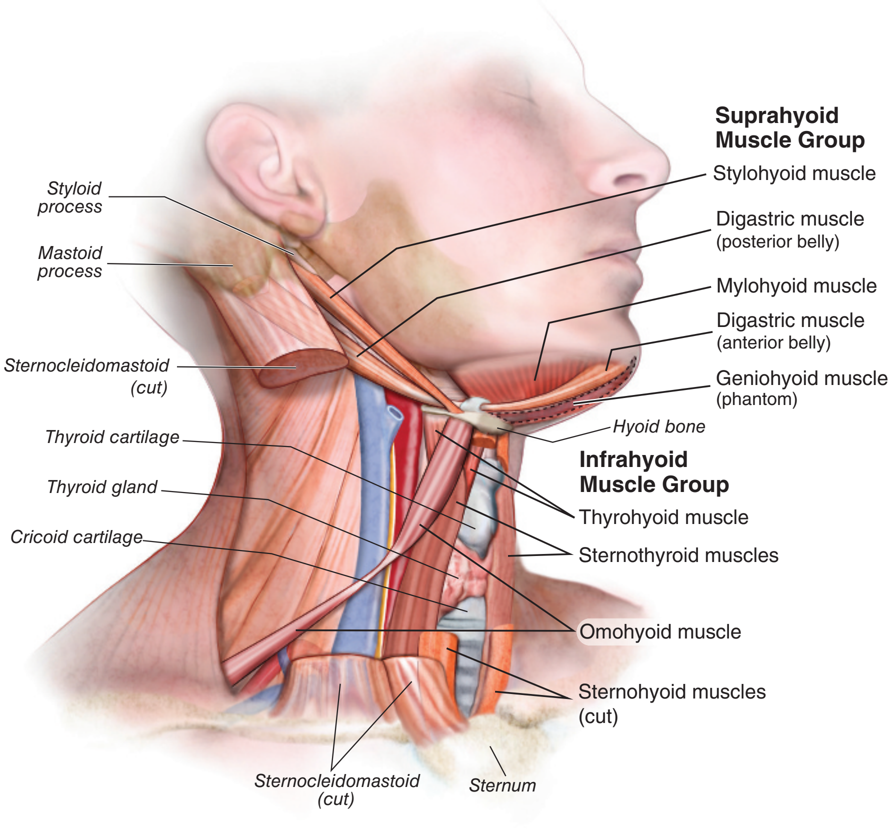
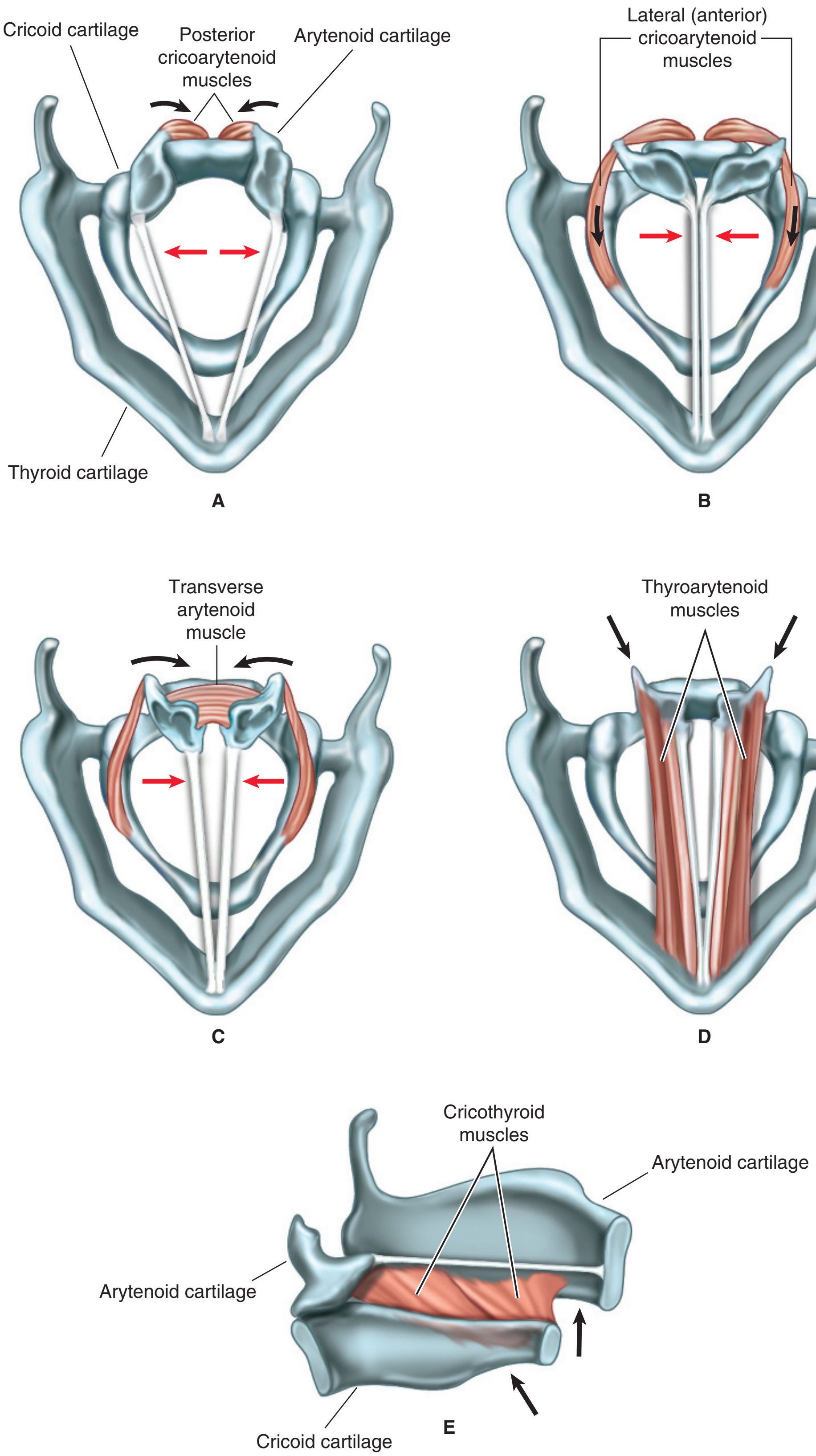

Suprahyoid Muscle Group
Stylohyoid muscle
Digastric muscle (posterior belly)
Mylohyoid muscle
Digastric muscle (anterior belly)
Geniohyoid muscle (phantom)
Hyoid bone
Infrahyoid Muscle Group
Thyrohyoid muscle
Sternothyroid muscles
Omohyoid muscle
Sternohyoid muscles (cut)
Sternum
Sternocleidomastoid (cut)
Styloid process
Mastoid process
Sternocleidomastoid (cut)
Thyroid cartilage
Thyroid gland
Cricoid cartilage

FIGURE 1-24 Intrinsic laryngeal muscles.


Cricoid cartilage
Posterior cricoarytenoid muscles
Arytenoid cartilage
Thyroid cartilage
A
Lateral (anterior) cricoarytenoid muscles
B
Transverse arytenoid muscle
C
Thyroarytenoid muscles
D
Cricothyroid muscles
Arytenoid cartilage
Arytenoid cartilage
Cricoid cartilage
E

Cricothyroid Muscles. These muscles, which are located on the anterior surface of the larynx, can swing the entire thyroid cartilage anteriorly. This action provides an additional way to tense the vocal folds and thereby change the frequency of phonation (Figure 1–24E).

Ventilatory Function of the Larynx

A primary function of the larynx is to ensure a free flow of air to and from the lungs. During a quiet inspiration, the vocal folds move apart (abduct) and widen the glottis. During exhalation, the vocal folds move slightly toward the midline (adduct) but always maintain an open glottal airway.

A second vital function of the larynx is effort closure during exhalation, also known as Valsalva's maneuver. During this maneuver, there is a massive undifferentiated adduction of the laryngeal walls, including both the true and false vocal folds. As a result, the lumen of the larynx is tightly sealed, preventing air from escaping during physical work such as lifting, pushing, coughing, throat-clearing, vomiting, urination, defecation, and parturition.

The Lower Airways

The Tracheobronchial Tree

After passing through the larynx, inspired air enters the tracheobronchial tree, which consists of a series of branching airways commonly referred to as generations, or orders. These airways become progressively narrower, shorter, and more numerous as they branch throughout the lungs (Figure 1–25). Table 1–1 lists the major subdivisions of the tracheobronchial tree.

FIGURE 1–25 Tracheobronchial tree.

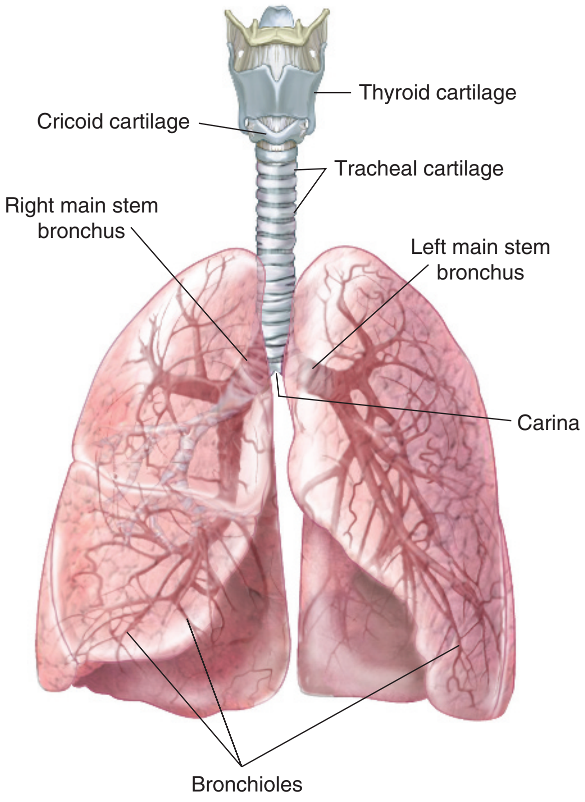


TABLE 1-1 Major Structures and Corresponding Generations of the Tracheobronchial Tree

	Structures of the Lungs	Generations[*]	
Conducting Zone	Trachea	0	Cartilaginous airways
	Main stem bronchi	1	
	Lobar bronchi	2	
	Segmental bronchi	3	
	Subsegmental bronchi	4–9	
	Bronchioles	10–15	Noncartilaginous airways
	Terminal bronchioles	16–19	
Respiratory Zone	Respiratory bronchioles[†]	20–23	Sites of gas exchange
	Alveolar ducts[†]	24–27	
	Alveolar sacs[†]	28	

[*] NOTE: The precise number of generations between the subsegmental bronchi and the alveolar sacs is not known.

[†] These structures collectively are referred to as a primary lobule (see The Sites of Gas Exchange) or lung parenchyma; they are also called terminal respiratory units and functional units.

In general, the airways exist in two major forms: (1) cartilaginous airways and (2) noncartilaginous airways. (The main structures of these airways are discussed in detail in The Lower Airways.) The cartilaginous airways serve only to conduct air between the external environment and the sites of gas exchange. The noncartilaginous airways serve both as conductors of air and as sites of gas exchange. These will be discussed in detail later.

Histology of the Tracheobronchial Tree

The tracheobronchial tree is composed of three layers: an epithelial lining, the lamina propria, and a cartilaginous layer (Figure 1–17 on page 18).

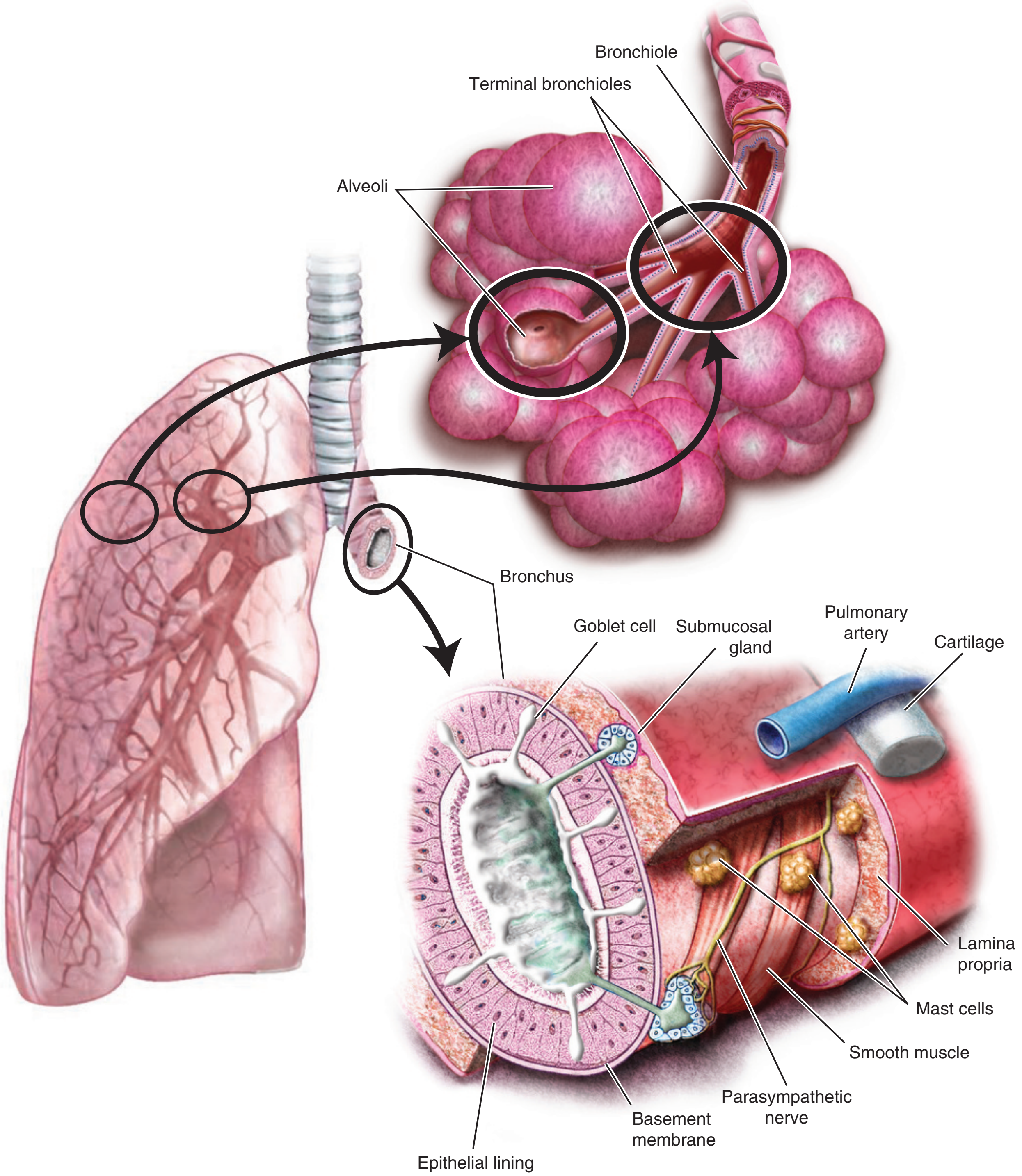
The Epithelial Lining. The epithelial lining is predominantly composed of pseudostratified ciliated columnar epithelium interspersed with numerous mucous glands and separated from the lamina propria by a basement membrane (see Figure 1–26). Along the basement membrane of the epithelial lining are oval-shaped basal cells. These cells serve as a reserve supply of cells and replenish the superficial ciliated cells and mucous cells as needed.

The pseudostratified ciliated columnar epithelium extends from the trachea to the respiratory bronchioles. There are about 200 cilia per ciliated cell. The length of each cilium is about 5 to 7 mm (microns). As the bronchioles become progressively smaller, the columnar structure of the epithelium decreases in height and appears more cuboidal than columnar (see Figure 1–6C). The cilia progressively disappear in the terminal bronchioles and are completely absent in the respiratory bronchioles.

A mucous layer, commonly referred to as the mucous blanket, covers the epithelial lining of the tracheobronchial tree (Figure 1–27).

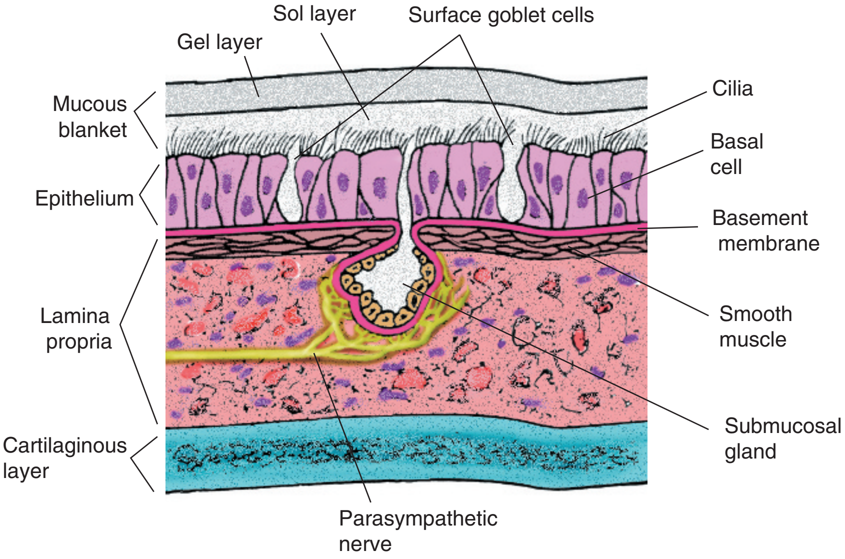
In general, the mucous blanket is composed of 95 percent water, with the remaining 5 percent consisting of glycoproteins, carbohydrates, lipids, DNA, some cellular debris, and foreign particles. The mucous is produced by (1) the goblet cells and (2) the submucosal, or bronchial, glands (see Figure 1–26). The goblet cells are located intermittently between the pseudostratified ciliated columnar cells and have been identified down to, and including, the terminal bronchioles. They empty when stimulated by infection or

FIGURE 1–26 Histology of the tracheobronchial tree.


Bronchiole
Terminal bronchioles
Alveoli
Bronchus
Goblet cell
Submucosal gland
Pulmonary artery
Cartilage
Lamina propria
Mast cells
Smooth muscle
Parasympathetic nerve
Basement membrane
Epithelial lining

inhaled smoke or dust. The submucosal glands, which produce most of the mucous blanket, extend deep into the lamina propria. These glands are innervated by the vagal parasympathetic nerve fibers (the tenth cranial nerve) and produce about 100 mL of bronchial secretions per day. Increased sympathetic activity decreases glandular secretions. The submucosal glands are particularly numerous in the medium-sized bronchi and disappear in the distal terminal bronchioles (see Figure 1–27).

FIGURE 1-27 Epithelial lining of the tracheobronchial tree.



The viscosity of the mucous blanket progressively increases from the epithelial lining to the inner luminal surface. The blanket has two distinct layers: (1) the sol layer, which is adjacent to the epithelial lining, and (2) the gel layer, which is the more viscous layer adjacent to the inner luminal surface. Under normal circumstances, the cilia move in a wavelike fashion through the less viscous sol layer and continually strike the innermost portion of the gel layer (approximately 1500 times per minute). This action propels the mucous layer, along with any foreign particles stuck to the gel layer, toward the larynx at an estimated average rate of 2 cm per minute. Precisely what causes the cilia to move is unknown. At the larynx, the cough mechanism moves secretions beyond the larynx and into the oropharynx. This process is commonly referred to as the mucociliary transport mechanism, or the mucociliary escalator, and is an important part of the cleansing mechanism of the tracheobronchial tree.

The Lamina Propria. The lamina propria is the submucosal layer of the tracheobronchial tree. Within the lamina propria there is a loose, fibrous tissue that contains tiny blood vessels, lymphatic vessels, and branches of the vagus nerve. Also found within the lamina propria are two sets of smooth-muscle fibers.

Clinical Connection 1-13

Excessive Airways Secretions

Bronchial irritation, inflammation, and excessive bronchial secretions commonly develop in a number of respiratory disorders—such as cystic fibrosis (Figure 1–28). If left untreated, thick and immobile secretions rapidly lead to (1) excessive accumulation, (2) partial airways obstruction and air trapping, (3) alveolar hyperinflation, or (4) complete airways obstruction and airways collapse. The respiratory therapist must always be aware that excessive bronchial secretions can adversely affect—or completely block—alveolar gas exchange. Various respiratory therapy modalities—such as postural drainage and chest percussion—should be activated as soon as possible to correct any of the problems associated with excessive airways secretions.

Excessive airways secretions also increase the patient's airways resistance to gas flow and, therefore, diminish the cough effectiveness. In addition, bacterial infections of the airways are more likely when excessive bronchial secretions are

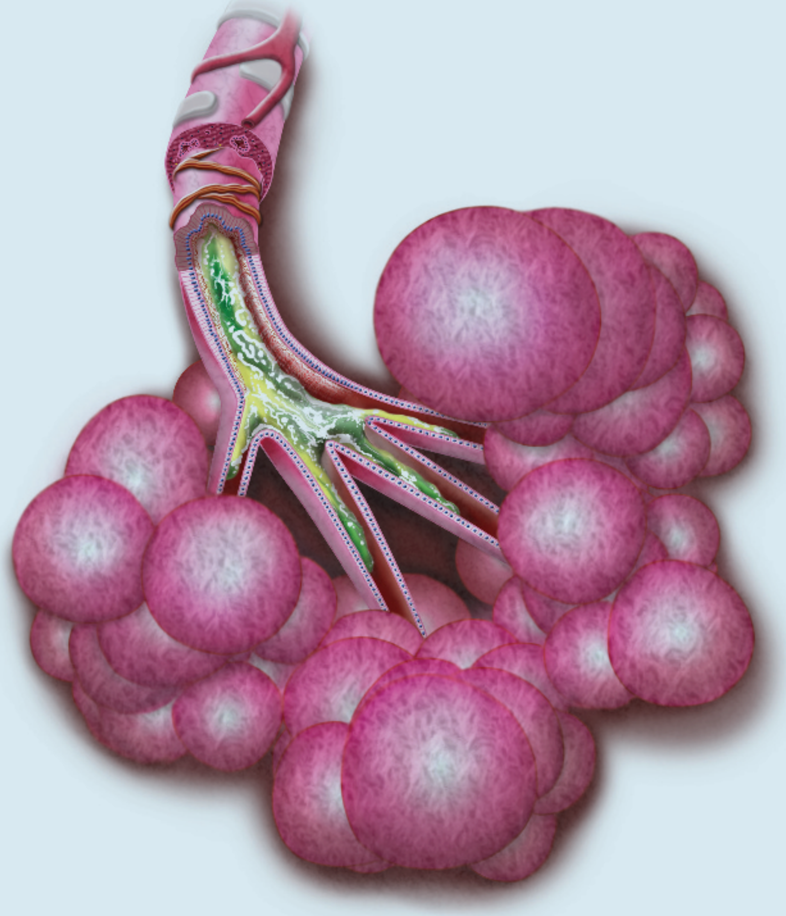
Clinical Connection 1-13, Continued

chronically present. When a bacterial infection is present, the patient's secretions will appear green and yellow. At the bedside, patients with excessive airways secretions commonly demonstrate a noisy, moist-sounding cough. The cough usually produces secretions. When listening to the patient's chest with a stethoscope, coarse, "bubbly" sounds (called course crackles) are often heard over large airways during exhalation. In addition, over the small and medium-sized airways, fine and crackling wet sounds (called crackles) are typically heard during inspiration.

Depending on the nature and severity of the disorder, the bronchial secretions may take several forms. For example, during the early stages of bronchitis, the secretions usually appear clear, thin, and odorless. During the late stages, the secretions are often copious, thick, and yellow and green in appearance—the classic sign of bacterial infection.

Clinically, there are many good therapeutic approaches used to mobilize excessive bronchial secretions. These therapies include (1) postural drainage therapy (the use of patient positioning to enhance gravitational drainage, may also be accompanied with chest percussion or vibration), (2) cough and deep breathing techniques, (3) positive airways pressure therapies (e.g., positive airways pressure [PAP] or continuous positive airways pressure [CPAP]), (4) high-frequency compression/oscillation mechanical ventilation procedures, (5) mobilization and exercise techniques, and (6) tracheobronchial tree suctioning.

FIGURE 1-28 Cystic fibrosis. Pathology includes (1) excessive production and accumulation of thick bronchial secretions, (2) partial bronchial obstruction and air trapping, (3) alveolar hyperinflation, and (4) complete airways obstruction and alveolar collapse.



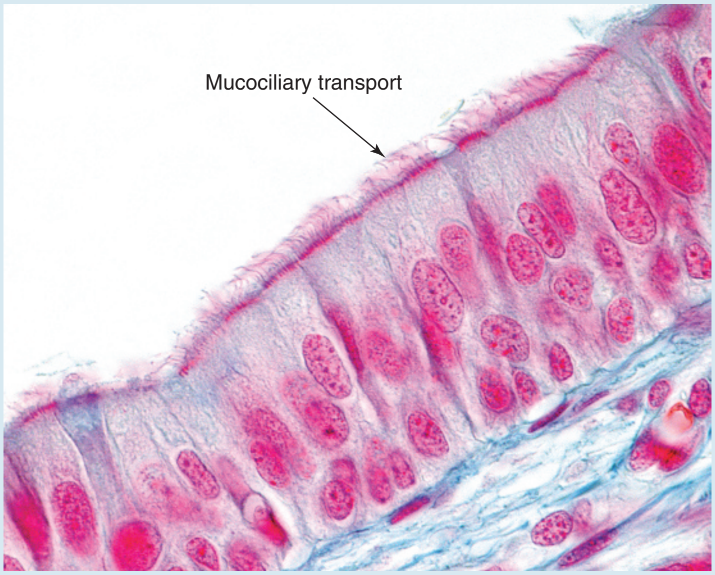
Clinical Connection 1-14

Abnormal Mucociliary Transport Mechanism

There are a number of abnormal conditions that can significantly slow the rate of the mucociliary transport mechanisms (Figure 1–29). Such conditions include the excessive bronchial secretions associated with chronic bronchitis, emphysema, bronchiectasis, and cystic fibrosis. Additional risk factors known to irritate and inflame the bronchial airways are tobacco smoke, dehydration, positive-pressure ventilation, endotracheal suctioning, high inspired oxygen concentrations, hypoxia, occupational dusts, irritating chemical vapors, indoor air pollution (e.g., biomass fuel used for cooking and heating), outdoor air pollution (e.g., silicates, sulfur dioxide, nitrogen oxides, and ozone), general anesthetic, and parasympatholytic drugs (e.g., atropine).

When the mucociliary escalator is compromised, coughing is the only means to mobilize secretions. For this reason, individuals with a depressed mucociliary transport—for any reason—should avoid medications that depress the cough reflex. In addition, the respiratory care practitioner will likely need to activate and/or up-regulate the patient's bronchial hygiene therapy (see common therapeutic approaches used to mobilize excessive bronchial secretions, Clinical Connection 1–13: Excessive Airways Secretions).

FIGURE 1-29 Mucociliary transport mechanism.



istockphoto.com/JOSE LUIS CALVO MARTIN & JOSE ENRIQUE GARCIA-MAURIÑO MUZQUIZ

These sets of muscles wrap around the tracheobronchial tree in fairly close spirals, one clockwise and the other counterclockwise. The smooth-muscle fibers extend down to, and include, the alveolar ducts (see the section on sites of gas exchange in this chapter). The outer portion of the lamina propria is surrounded by a thin connective tissue layer called the peribronchial sheath.

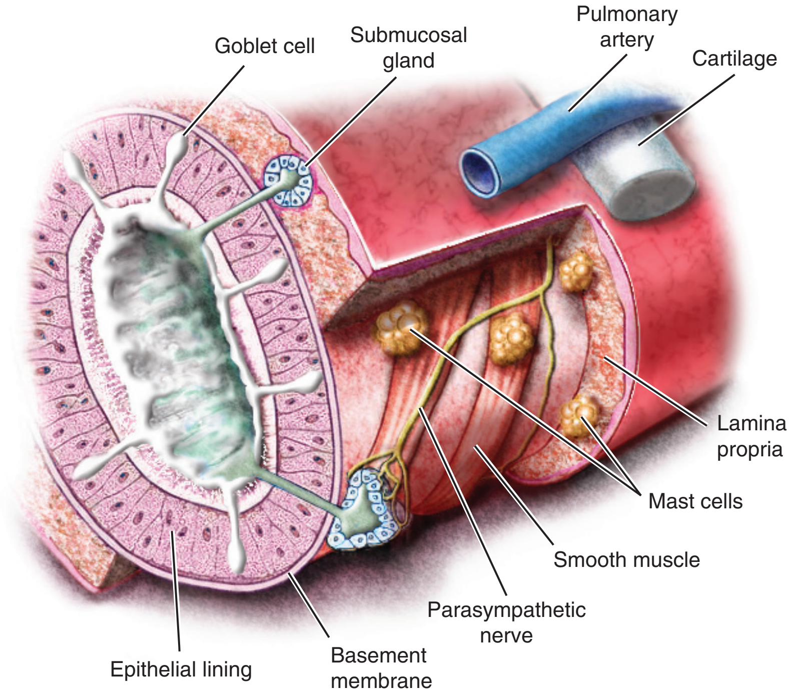
Immune Response. Mast cells play an important role in the immunologic mechanism. Mast cells are found in the lamina propria—near the branches of the vagus nerve and blood vessels and scattered throughout the smooth-muscle bundles, in the intra-alveolar septa, and as one of the cell constituents of the submucosal glands (Figure 1–30). Outside of the lungs, mast cells are found in the loose connective tissue of the skin and intestinal submucosa.

When they are activated, numerous substances are released from the mast cells that can significantly alter the diameter of the bronchial airways. Because of this fact, a basic understanding of how the mast cells function in the immunologic system is essential for the respiratory therapist.

There are two major immune responses: cellular immunity and humoral immunity. The **cellular immune response** involves the sensitized lymphocytes that are responsible for tissue rejection in transplants. This immune response is also termed a type IV, or delayed, type of hypersensitivity.

The **humoral immune response** involves the circulating antibodies that are involved in allergic responses such as allergic asthma. Antibodies (also called immunoglobulins) are serum globulins, or proteins, that defend against invading environmental antigens such as pollen, animal dander, and feathers. Although five

FIGURE 1–30 Cross-section of a bronchus showing the mast cells in the lamina propria.

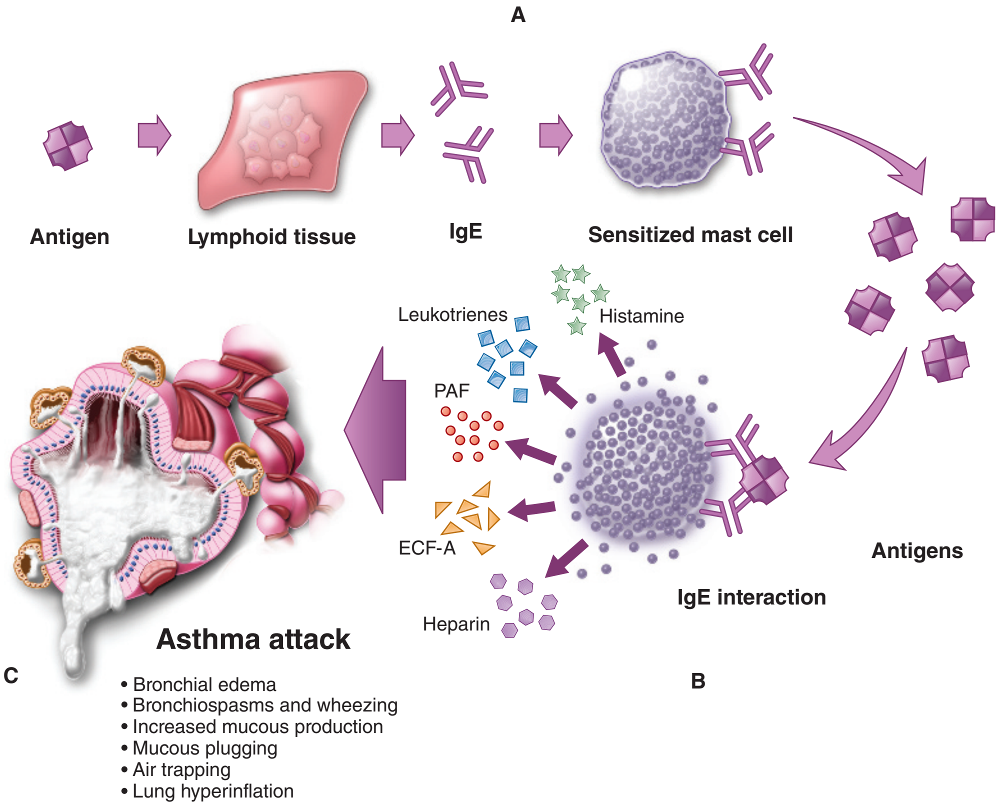


different immunoglobulins (IgG, IgA, IgM, IgD, and IgE) have been identified, the IgE (reaginic) antibody is basic to the allergic response. The mechanism of the IgE antibody–antigen reaction is as follows:

1. When a susceptible individual is exposed to a certain antigen, the lymphoid tissues release specific IgE antibodies. The newly formed IgE antibodies travel through the bloodstream and attach to surface receptors on the mast cells. It is estimated that there are between 100,000 and 500,000 IgE receptor sites on the surface of each mast cell. Once the IgE antibodies attach to the mast cell, the individual (or more specifically, the mast cell) is said to be sensitive to the specific antigen (Figure 1–31A).
2. Each mast cell also has about 1000 secretory granules that contain several chemical mediators of inflammation. Continued exposure, or reexposure, to the same antigen creates an IgE antibody–antigen reaction on the surface of the mast cell, which works to destroy or inactivate the antigen. This response, however, causes the mast cell to degranulate (break down) and to release the following chemical mediators (Figure 1–31B):
    a. Histamine
    b. Heparin
    c. Platelet-activating factor (PAF)
    d. Eosinophilic chemotactic factor of anaphylaxis (ECF-A)
    e. Leukotrienes
3. The release of these chemical mediators causes increased vascular permeability, smooth-muscle contraction, increased mucous secretion, and vasodilation with edema.

Such a reaction in the lungs can be extremely dangerous and is seen in individuals during an allergic asthmatic episode. The production of IgE antibodies may be 20 times greater than normal in some patients with asthma (the normal IgE antibody level in the serum is about 200 ng/mL). During an asthmatic attack, the patient demonstrates bronchial edema, bronchospasms and wheezing, increased mucous production, mucous plugging, air trapping, and lung hyperinflation (Figure 1–31C).

FIGURE 1-31 Immunologic mechanisms.


A
Antigen
Lymphoid tissue
IgE
Sensitized mast cell
Leukotrienes
Histamine
PAF
ECF-A
Heparin
IgE interaction
Antigens
B
C
Asthma attack
• Bronchial edema
• Bronchiospasms and wheezing
• Increased mucous production
• Mucous plugging
• Air trapping
• Lung hyperinflation

The Cartilaginous Layer. The cartilaginous layer, which is the outermost layer of the tracheobronchial tree, progressively diminishes in size as the airways extend into the lungs. Cartilage is completely absent in bronchioles less than 1 mm in diameter (see Figure 1–26).

The Cartilaginous Airways

As shown in Table 1–1, the cartilaginous airways consist of the trachea, main stem bronchi, lobar bronchi, segmental bronchi, and subsegmental bronchi. Collectively, the cartilaginous airways are referred to as the conducting zone.

Trachea. The adult trachea is about 11 to 13 cm long and 1.5 to 2.5 cm in diameter (Figure 1–32). It extends vertically from the cricoid cartilage of the larynx to about the level of the second costal cartilage, or fifth thoracic vertebra. At this point, the trachea divides into the right and left main stem bronchi. The bifurcation of the trachea is known as the carina. Approximately 15 to 20 C-shaped cartilages support the trachea. These cartilages are incomplete posteriorly where the trachea and the esophagus share a fibro-elastic membrane (Figure 1–33).

Main Stem Bronchi. The right main stem bronchus branches off the trachea at about a 25-degree angle; the left main stem bronchus forms an angle of 40 to 60 degrees with the trachea. The right main stem bronchus is wider, more vertical, and about 5 cm shorter than the left main stem bronchus. It should be noted that because the right main stem bronchus is wider—and more vertical—than the left main stem bronchus, the respiratory therapist must always make certain that the endotracheal tube has not been over-advanced into the right main stem bronchus during intubation. Similar to the trachea, the main stem bronchi are supported by C-shaped cartilages. In the newborn, both the right and left main stem bronchi form about a 55-degree angle with the trachea. The main stem bronchi are the tracheobronchial tree's first generation.

FIGURE 1-32 Tracheobronchial tree.

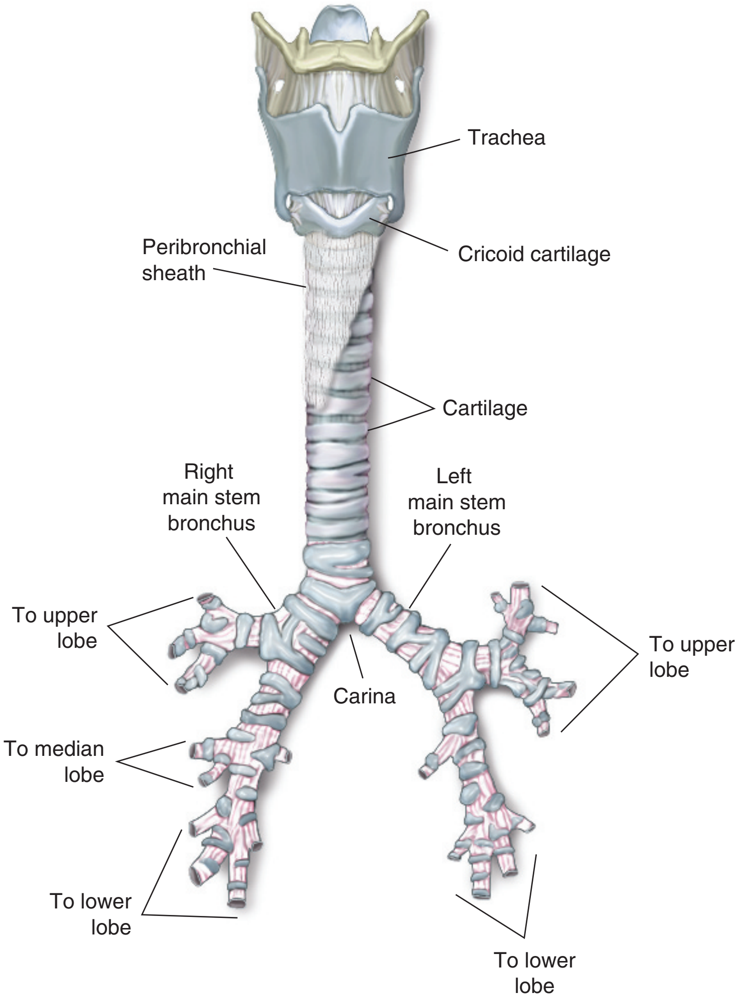
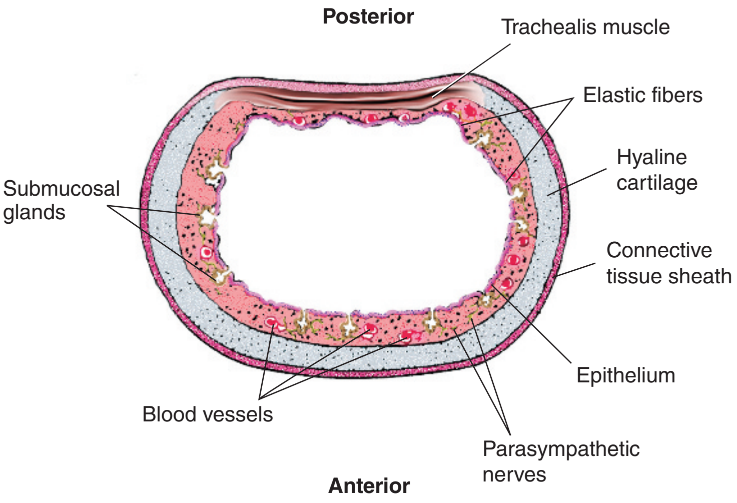

Trachea
Peribronchial sheath
Cricoid cartilage
Cartilage
Right main stem bronchus
Left main stem bronchus
To upper lobe
To upper lobe
Carina
To median lobe
To lower lobe
To lower lobe

FIGURE 1-33 Cross-section of the trachea.


Posterior
Trachealis muscle
Elastic fibers
Hyaline cartilage
Submucosal glands
Connective tissue sheath
Epithelium
Blood vessels
Parasympathetic nerves
Anterior

Clinical Connection 1-15

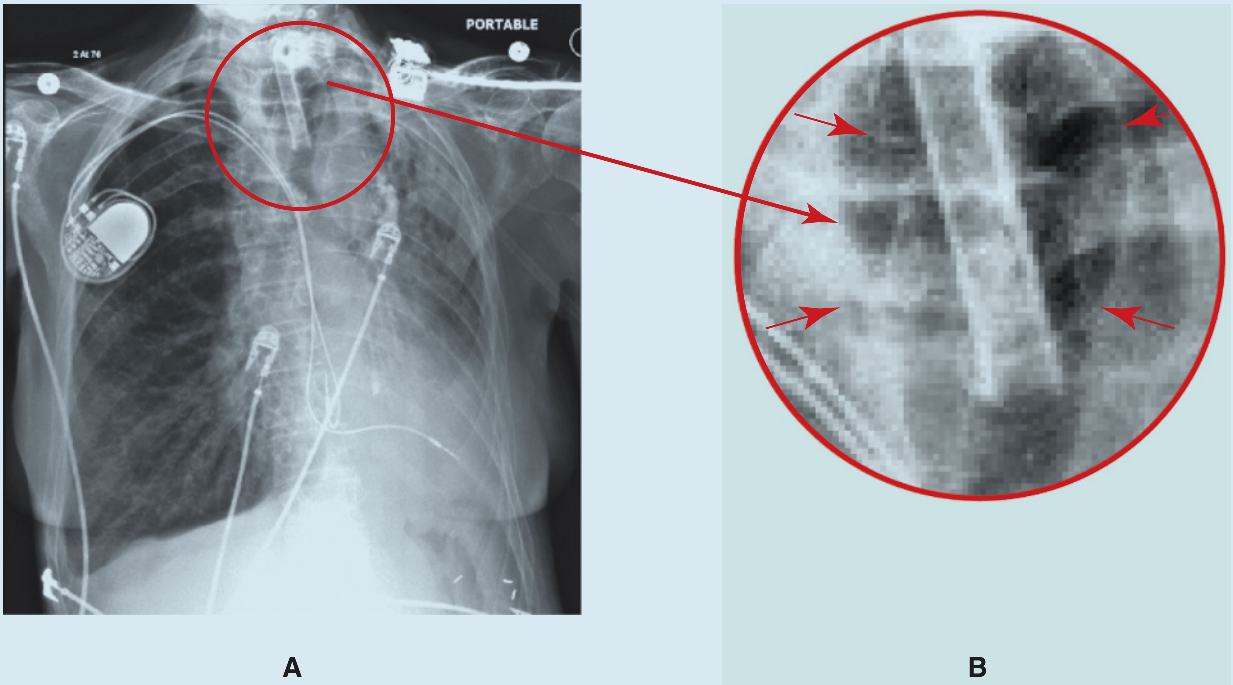
Hazards Associated with Endotracheal Tubes

Endotracheal tube cuffs are used to seal the airways to (1) adequately apply positive pressure mechanical ventilation and (2) prevent aspiration. The respiratory therapist must carefully monitor and maintain the cuff pressure below the tracheal mucosal capillary blood pressure—estimated to range between 25 and 30 mm Hg under normal conditions. Clinically, the recommended "safe range" is a cuff pressure between 20 and 25 mm Hg. Should the lateral cuff pressure exceed the tracheal blood pressure, the tracheal mucosal blood supply—immediately adjacent to the tube cuff—will be inadequate or completely blocked off. Prolonged and excessive cuff pressure can lead to tracheal mucosal ischemia, inflammation, necrosis, ulceration, and destruction of the tracheal wall cartilage.

When the preceding chain of events occurs, any number of additional harmful conditions can develop—including tracheal dilatation and erosion. Tracheal erosion can ultimately lead to a **fistula**—that is, an abnormal communication between the trachea and a nearby structure. Common fistulas associated with tracheal cuff erosions are the **innominate artery** (tracheoinnominate fistula) and the **esophagus** (tracheoesophageal fistula). In fact, the innominate artery is the most common artery involved in massive hemorrhage associated with a tracheostomy.

Figure 1–34 shows a chest X-ray of a patient who managed—and, unfortunately, overinflated and overpressurized—her own tracheal tube cuff at home. At the time of this X-ray, the excessive cuff pressure had already significantly dilated the trachea and eroded into her esophagus, causing a tracheoesophageal fistula. Figure 1–35 shows the close anatomic proximity of a tracheostomy tube cuff and the innominate artery and esophagus.

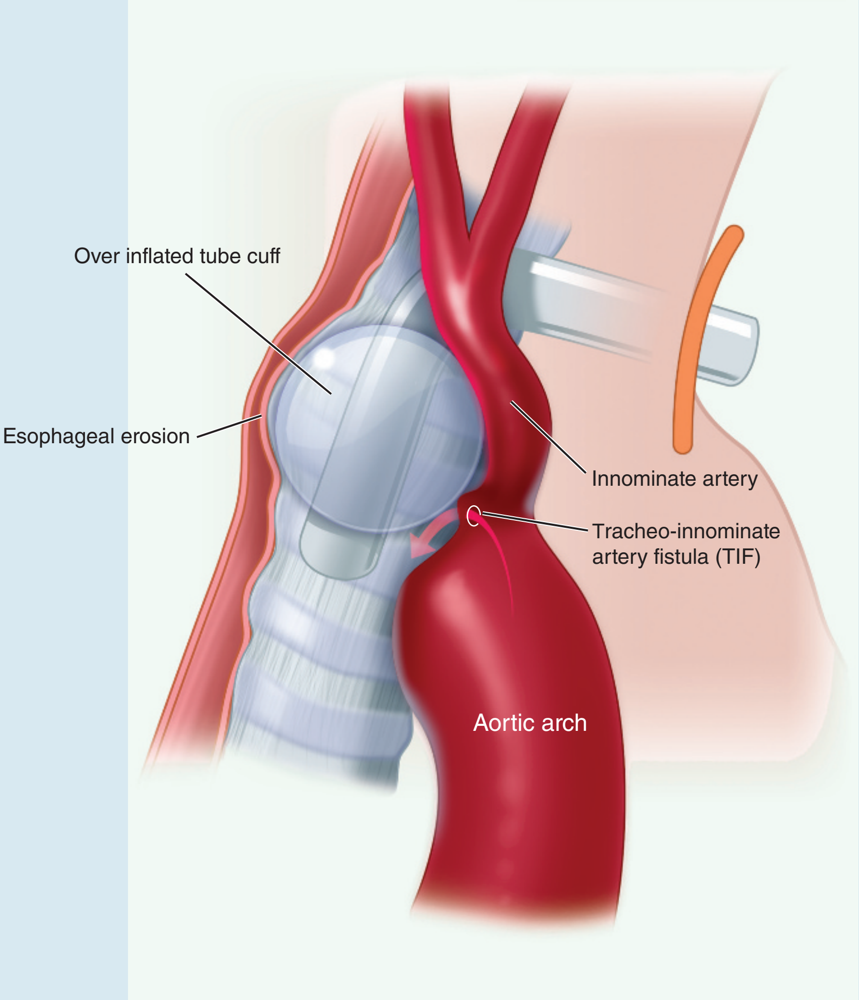
FIGURE 1-34 **A.** A 48-year-old female who managed—and, unfortunately, overinflated and overpressurized—her tracheal tube at home. **B.** Note the close-up of the dilated trachea (red arrows and dark area) around the tracheal tube. Note: Only the tracheal tube can be seen. The cuff does not appear on chest X-rays, because it is primarily composed on air.



Courtesy T. Des Jardins, WindMist LLC

Clinical Connection 1-15, Continued

FIGURE 1-35 The close anatomic proximity of a tracheostomy tube cuff and the innominate artery and esophagus.


Over inflated tube cuff
Esophageal erosion
Innominate artery
Tracheo-innominate artery fistula (TIF)
Aortic arch

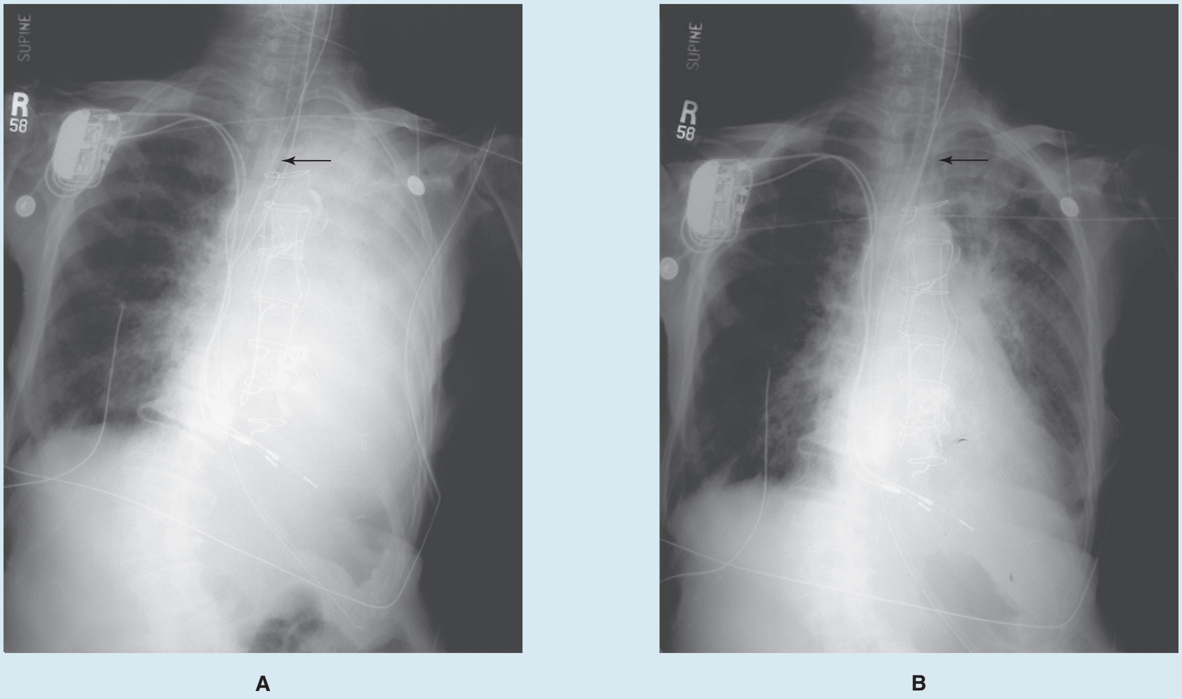
Clinical Connection 1-16

Inadvertent Intubation of Right Main Stem Bronchus

Clinically, the tip of the endotracheal tube should be about 4 to 6 cm above the carina, or between the second and fourth tracheal. The correct position of the endotracheal tube is verified with a chest radiograph (i.e., the tip of the tube can be seen about 4 to 6 cm above the carina). When an endotracheal tube is inserted too deeply (beyond the carina), it most commonly enters the right main stem bronchus. When this occurs, the left lung receives little or no ventilation and alveolar collapse (atelectasis) ensues (Figure 1–36A). When this condition is identified (via a chest X-ray or absence of breath sounds over the left lung), the endotracheal tube should be pulled back immediately (Figure 1–36B).

Clinical Connection 1-16, Continued

FIGURE 1-36 Chest radiograph of 86-year-old post-open-heart surgical patient. **A.** The endotracheal tube tip in the right mainstem bronchus (see arrow). Because of the preferential ventilation to the right lung, atelectasis and volume "loss" is present in the patient's left lung (i.e., white fluffy areas in left lung). **B.** The same patient 20 minutes after the endotracheal tube was pulled back above the carina (see arrow). Note that the patient's left lung is now better ventilated (i.e., increased darker area in the left lung).



Lobar Bronchi. The right main stem bronchus divides into the upper, middle, and lower lobar bronchi. The left main stem bronchus branches into the upper and lower lobar bronchi. The lobar bronchi are the tracheobronchial tree's second generation. The C-shaped cartilages that support the trachea and the main stem bronchi progressively form cartilaginous plates around the lobar bronchi.

Segmental Bronchi. A third generation of bronchi branch off the lobar bronchi to form the segmental bronchi. There are 10 segmental bronchi in the right lung and 8 in the left lung. Each segmental bronchus is named according to its location within a particular lung lobe.

Subsegmental Bronchi. The tracheobronchial tree continues to subdivide between the fourth and approximately the ninth generation into progressively smaller airways called subsegmental bronchi. These bronchi range in diameter from 1 to 4 mm. Peribronchial connective tissue containing nerves, lymphatics, and bronchial arteries surround the subsegmental bronchi to about the 1-mm diameter level. Beyond this point, the connective tissue sheaths disappear.

The Noncartilaginous Airways

The noncartilaginous airways are composed of the bronchioles and the terminal bronchioles.

Bronchioles. When the bronchi decrease to less than 1 mm in diameter and are no longer surrounded by connective tissue sheaths, they are called bronchioles. The bronchioles are found between the tenth and fifteenth generations. At this level, cartilage is absent and the lamina propria is directly connected with the lung parenchyma (see lung parenchyma in the section on sites of gas exchange in this chapter). The bronchioles are surrounded by spiral muscle fibers and the epithelial cells are more cuboidal in shape (see Figure 1–26). The rigidity of the bronchioles is low compared with the cartilaginous airways. Because of this, the airways patency at this level may be substantially affected by intra-alveolar and intrapleural pressures and by alterations in the size of the lungs. This lack of airways support often plays a major role in respiratory disease.

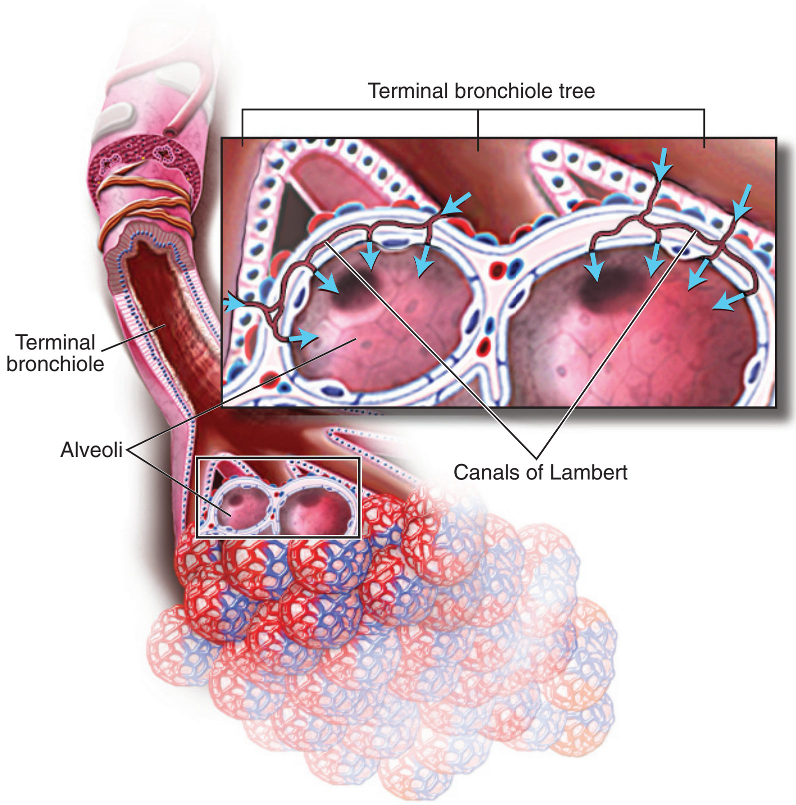
Terminal Bronchioles. The conducting tubes of the tracheobronchial tree end with the terminal bronchioles between the sixteenth and nineteenth generations. The average diameter of the terminal bronchioles is about 0.5 mm. At this point, the cilia and the mucous glands progressively disappear, and the epithelium flattens and becomes cuboidal in shape (see Figure 1–6C and Figure 1–26).

As the wall of the terminal bronchioles progressively becomes thinner, small channels, called the canals of Lambert, begin to appear between the inner luminal surface of the terminal bronchioles and the adjacent alveoli that surround them (Figure 1–37). Although specific information as to their function is lacking, it is believed that these tiny pathways may be important secondary avenues for collateral ventilation in patients with certain respiratory disorders (e.g., chronic obstructive pulmonary disease [COPD]).

Also unique to the terminal bronchioles is the presence of Clara cells. These cells have thick protoplasmic extensions that bulge into the lumen of the terminal bronchioles. The precise function of the Clara cells is not known. They may have secretory functions that contribute to the extracellular liquid lining the bronchioles and alveoli. They may also contain enzymes that work to detoxify inhaled toxic substances.

The structures beyond the terminal bronchioles are the sites of gas exchange and, although directly connected to it, are not considered part of the tracheobronchial tree.

FIGURE 1-37 Canals of Lambert.



Bronchial Cross-Sectional Area

The total cross-sectional area of the tracheobronchial tree steadily increases from the trachea to the terminal bronchioles. The total cross-sectional area increases significantly beyond the terminal bronchioles because of the many branches that occur at this level. The structures distal to the terminal bronchioles are collectively referred to as the respiratory zone (Figure 1–38).

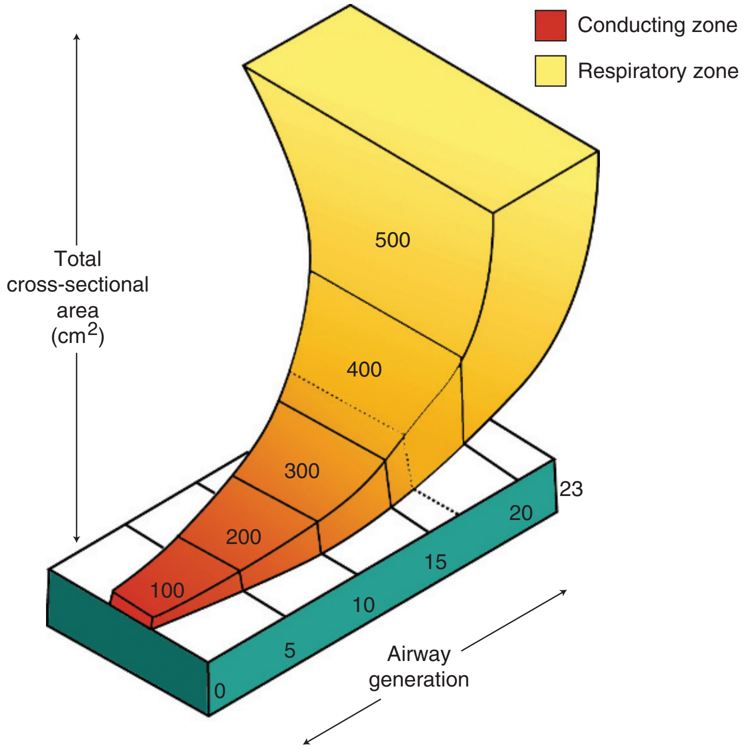
Air flows down the tracheobronchial tree as a mass to about the level of the terminal bronchioles, like water flowing through a tube. Because the cross-sectional area becomes so great beyond this point, however, the forward motion essentially stops and the molecular movement of gas becomes the dominant mechanism of ventilation.

Bronchial Blood Supply

The bronchial arteries nourish the tracheobronchial tree. The arteries arise from the aorta and follow the tracheobronchial tree as far as the terminal bronchioles. Beyond the terminal bronchioles, the bronchial arteries lose their identity and merge with the pulmonary arteries and capillaries, which are part of the pulmonary vascular system. The normal bronchial arterial blood flow is about 1 percent of the cardiac output. In addition to the tracheobronchial tree, the bronchial arteries nourish the mediastinal lymph nodes, the pulmonary nerves, a portion of the esophagus, and the visceral pleura.

About one-third of the bronchial venous blood returns to the right atrium by way of the azygos, hemiazygos, and intercostal veins. Most of this blood comes from the first two or three generations of the tracheobronchial tree. The remaining two-thirds of the bronchial venous blood drains into the pulmonary circulation, via bronchopulmonary anastomoses, and then flows to the left atrium by way of the pulmonary veins. In effect, the bronchial venous blood, which is low in oxygen and high in carbon dioxide, mixes

FIGURE 1–38 Cross-section of bronchial area. Note the rapid increase in the total cross-sectional area of the airways in the respiratory zone.



with blood that has just passed through the alveolar-capillary system, which is high in oxygen and low in carbon dioxide. The mixing of venous blood and freshly oxygenated blood is known as venous admixture. (The effects of venous admixture are discussed in greater detail in Chapter 6.)

The Sites of Gas Exchange

The structures distal to the terminal bronchioles are the functional units of gas exchange. They are composed of about three generations of respiratory bronchioles, followed by about three generations of alveolar ducts and, finally, ending in 15 to 20 grapelike clusters, the alveolar sacs (Figure 1–39). The respiratory bronchioles are characterized by alveoli budding from their walls. The walls of the alveolar ducts that arise from the respiratory bronchioles are completely composed of alveoli separated by septal walls that contain smooth-muscle fibers. Most gas exchange takes place at the alveolar-capillary membrane (Figure 1–40). In the lungs of the adult male, there are approximately 300 million alveoli between 75 and 300 µm in diameter, and small pulmonary capillaries cover about 85 to 95 percent of the alveoli. This arrangement provides an average surface area of 70 m^2 (about the size of a tennis court) available for gas exchange.

Collectively, the respiratory bronchioles, alveolar ducts, and alveolar clusters that originate from a single terminal bronchiole are referred to as a primary lobule. Each primary lobule is about 3.5 µm in diameter and contains about 2000 alveoli. It is estimated that there are approximately 130,000 primary lobules in the lung. Synonyms for *primary lobule* include *acinus*, *terminal respiratory unit*, *lung parenchyma*, and *functional units* (see Table 1–1).

FIGURE 1-39 Schematic of the structures distal to the terminal bronchioles; collectively, these are referred to as the primary lobule.

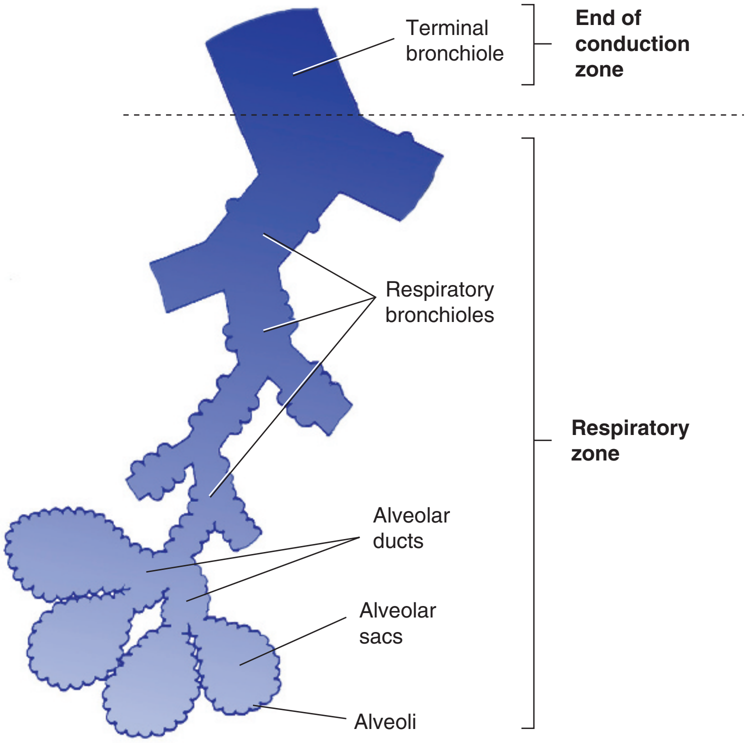
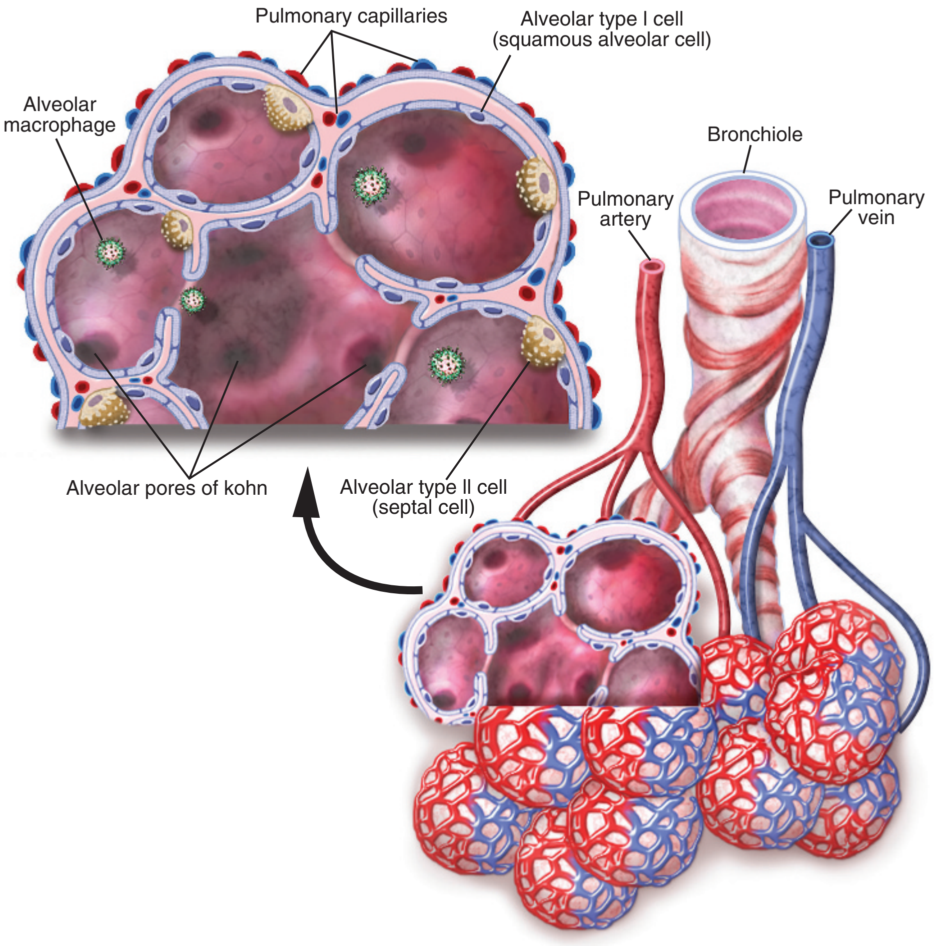


FIGURE 1-40 Alveolar-capillary network. The blow up of the alveolar-capillary network illustrates the (1) pulmonary capillaries, (2) alveolar type I cells (squamous alveolar cells), (3) alveolar type II cells (septal cells), (4) alveolar macrophage, and (5) alveolar pores of kohn.


Pulmonary capillaries
Alveolar type I cell (squamous alveolar cell)
Alveolar macrophage
Bronchiole
Pulmonary artery
Pulmonary vein
Alveolar pores of kohn
Alveolar type II cell (septal cell)

Alveolar Epithelium

The alveolar epithelium is composed of two principal cell types: the type I cell, or squamous pneumocyte, and the type II cell, or granular pneumocyte.

Type I cells are primarily composed of a cytoplasmic ground substance. They are broad, thin cells that form about 95 percent of the alveolar surface. They are 0.1 to 0.5 μm thick and are the major sites of alveolar gas exchange. Several type I cells connect edge to edge to form one or more alveoli. When type I cells die, they are replaced by type II cells that convert to type I cells. Type I cells are unable to reproduce, while type II cells can.

Type II cells form the remaining 5 percent of the total alveolar surface. They have microvilli and are cuboidal in shape. They are believed to be the primary source of pulmonary surfactant. Surfactant molecules are situated at the air–liquid interface of the alveoli and play a major role in decreasing the surface tension of the fluid that lines the alveoli (see Figure 1–40).

Pores of Kohn

The pores of Kohn are small holes in the walls of the interalveolar septa (see Figure 1–40). They are 3 to 13 μm in diameter and permit gas to move between adjacent alveoli. The formation of the pores may include one or more of the following processes: (1) the desquamation (i.e., shedding or peeling) of epithelial cells due to disease; (2) the normal degeneration of tissue cells as a result of age; and (3) the movement of macrophages, which may leave holes in the alveolar walls. Diseases involving the lung parenchyma accelerate the formation of alveolar pores of Kohn, and the number and size of the pores increase progressively with age.

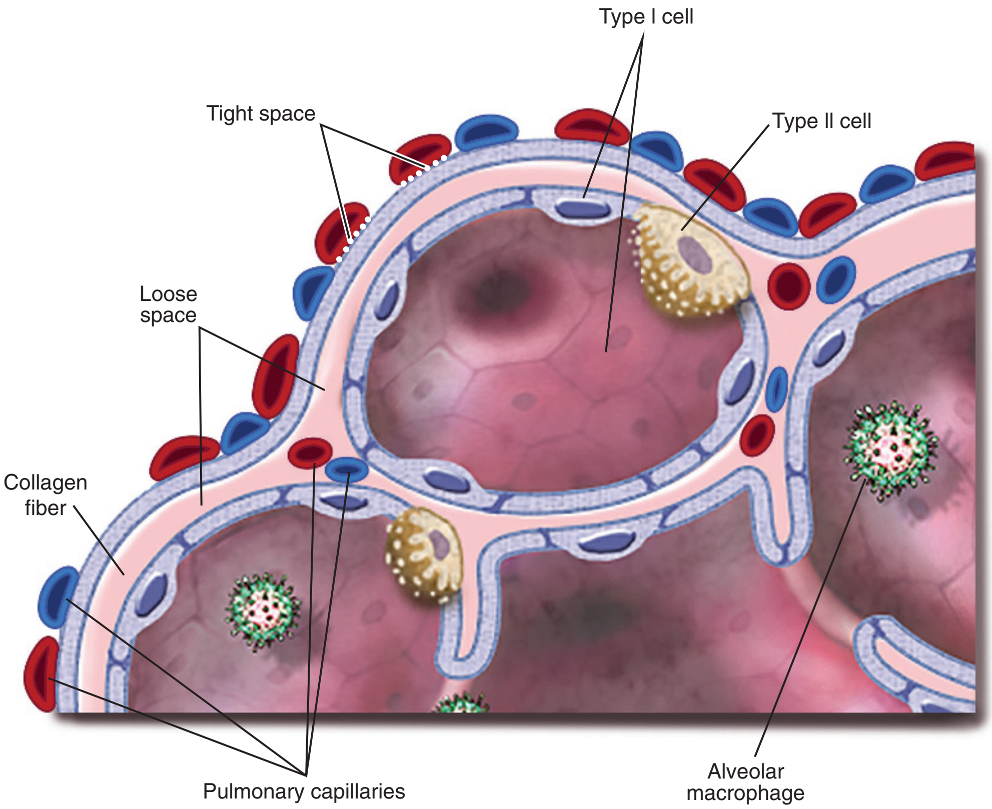
Alveolar Macrophages

Alveolar macrophages, or type III alveolar cells, play a major role in removing bacteria and other foreign particles that are deposited within the acini. Macrophages are believed to originate from stem cell precursors in the bone marrow. Then, as monocytes, they presumably migrate through the bloodstream to the lungs, where they move about or are embedded in the extracellular lining of the alveolar surface. There is also evidence that the alveolar macrophages reproduce within the lung (see Figure 1–40).

Interstitium

The alveolar-capillary clusters are surrounded, supported, and shaped by the interstitium (Figure 1–41). The interstitium is a gel-like substance composed of hyaluronic acid molecules that are held together by a weblike network of collagen fibers. The interstitium has two major compartments: the tight space and the loose space. The tight space is the area between the alveolar epithelium and the endothelium of the pulmonary capillaries—the area where most gas exchange occurs. The loose space is primarily the area that surrounds the bronchioles, respiratory bronchioles, alveolar ducts, and alveolar sacs. Lymphatic vessels and neural fibers are found in this area. Water content in this area can increase more than 30 percent before a significant pressure change develops.

FIGURE 1-41 Pulmonary interstitium. Most gas exchange occurs in the tight space area. The area around the respiratory bronchioles, alveolar ducts, and alveolar sacs is called the loose space.



The collagen in the interstitium is believed to limit alveolar distensibility. Expansion of a lung unit beyond the limits of the interstitial collagen can (1) occlude the pulmonary capillaries or (2) damage the structural framework of the collagen fibers and, subsequently, the wall of the alveoli.

The Pulmonary Vascular System*

The pulmonary vascular system delivers blood to and from the lungs for gas exchange. In addition to gas exchange, the pulmonary vascular system provides nutritional substances to the structures distal to the terminal bronchioles. Similar to the systemic vascular system, the pulmonary vascular system is composed of arteries, arterioles, capillaries, venules, and veins.

Arteries

The right ventricle of the heart pumps deoxygenated blood into the pulmonary artery. Just beneath the aorta the pulmonary artery divides into the right and left branches (Figure 1–42). The branches then penetrate their respective lung through the hilum, which is that part of the lung where the main stem bronchi, vessels, and nerves enter. In general, the pulmonary artery follows the tracheobronchial tree in a posterolateral relationship branching or dividing as the tracheobronchial tree does.

The pulmonary arteries have three layers of tissue in their walls (Figure 1–43). The inner layer is called the tunica intima and is composed of endothelium and a thin layer of connective and elastic tissue. The middle layer is called the tunica media and consists primarily of elastic connective tissue in large arteries and smooth muscle in medium-sized to small arteries. The tunica media is the thickest layer in the arteries. The outermost layer is called the tunica adventitia and is composed of connective tissue. This layer also contains small vessels that nourish all three layers. Because of the different layers, the arteries are relatively stiff vessels that are well suited for carrying blood under high pressures in the systemic system.

Arterioles

The walls of the pulmonary arterioles consist of an endothelial layer, an elastic layer, and a layer of smooth-muscle fibers (see Figure 1–43). The elastic and smooth-muscle fibers gradually disappear just before entering the alveolar-capillary system. The pulmonary arterioles supply nutrients to the respiratory bronchioles, alveolar ducts, and alveoli. By virtue of their smooth-muscle fibers, the arterioles play an important role in the distribution and regulation of blood and are called the resistance vessels.

Capillaries

The pulmonary arterioles give rise to a complex network of capillaries that surround the alveoli. The capillaries are composed of an endothelial layer (a single layer of squamous epithelial cells) (see Figure 1–43). The capillaries are essentially an extension of the inner lining of the larger vessels. The walls of the pulmonary capillaries are less than 0.1 μm thick, and the external diameter of each vessel is about 10 μm. The capillaries are where gas exchange occurs. The pulmonary capillary endothelium also has a selective permeability to substances such as water, electrolytes, and sugars.

In addition to gas and fluid exchange, the pulmonary capillaries play an important biochemical role in the production and destruction of a broad range of biologically active substances. For example, serotonin, norepinephrine, and some prostaglandins are destroyed by the pulmonary capillaries.

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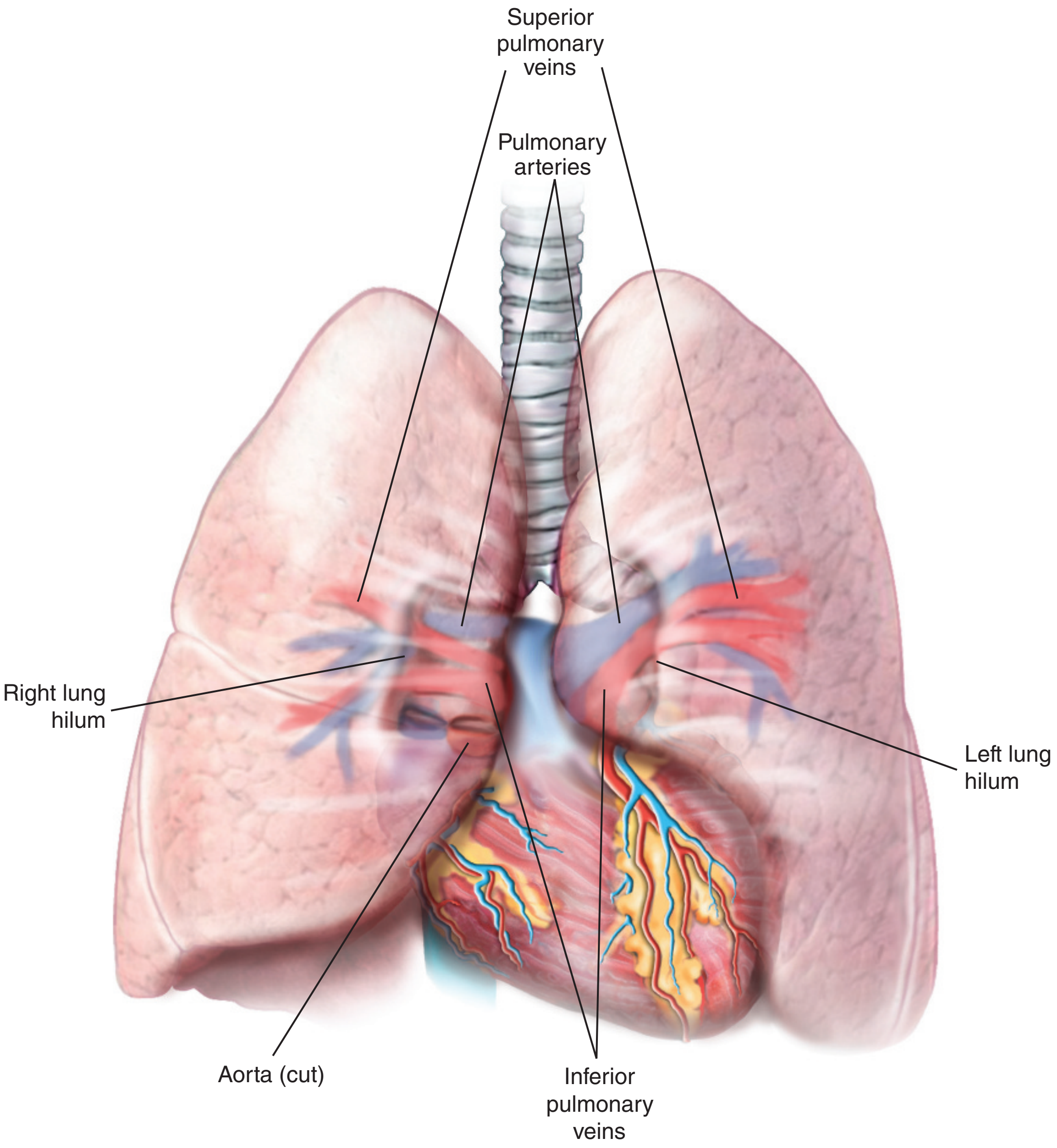
*Refer to Chapter 5 for a more comprehensive presentation of the pulmonary vascular system.

FIGURE 1-42 Major pulmonary vessels.


Superior pulmonary veins
Pulmonary arteries
Right lung hilum
Left lung hilum
Aorta (cut)
Inferior pulmonary veins

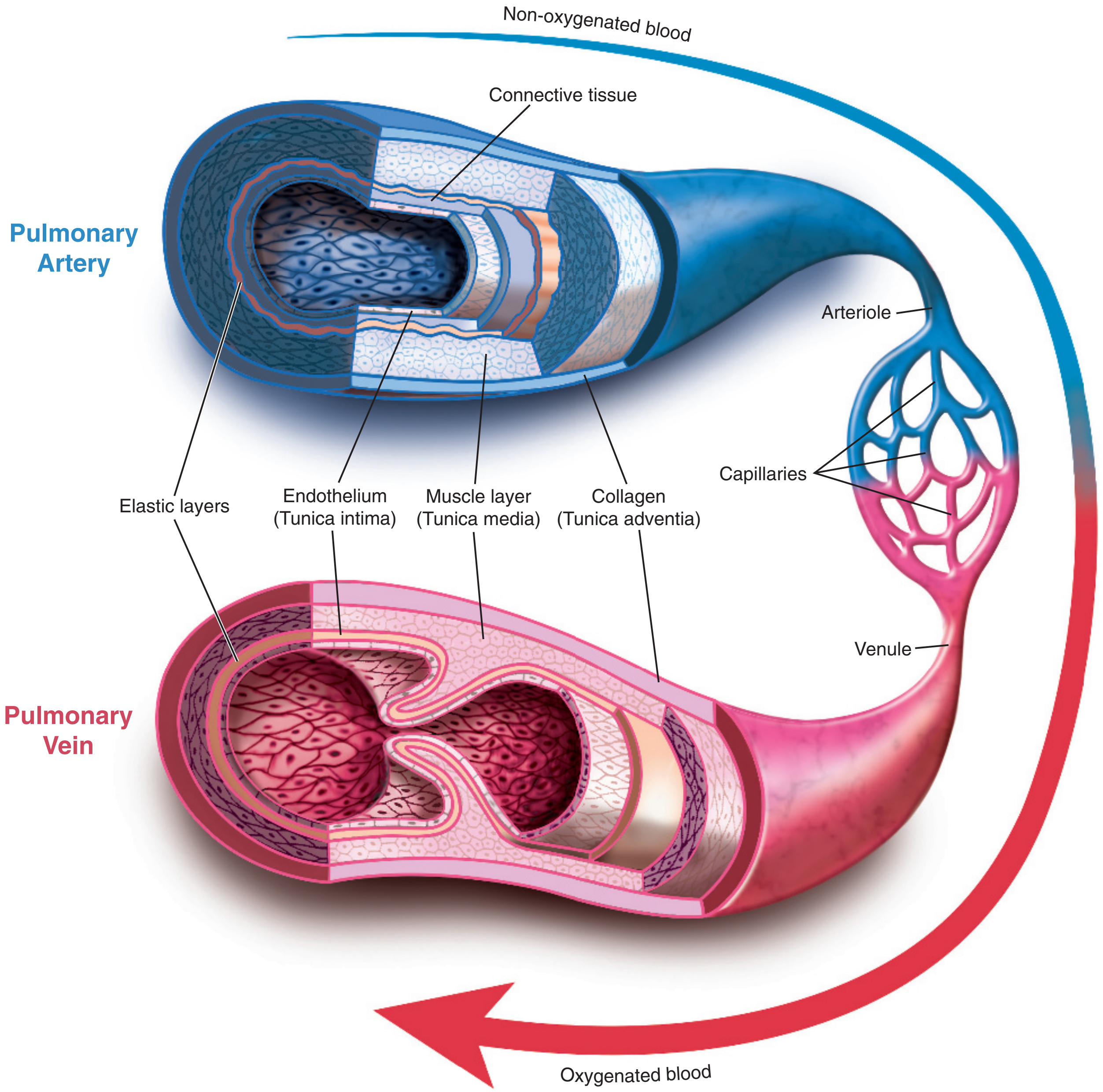
Some prostaglandins are produced and synthesized by the pulmonary capillaries, and some circulating inactive peptides are converted to their active form; for example, the inactive angiotensin I is converted to the active angiotensin II.

Venules and Veins

After blood moves through the pulmonary capillaries, it enters the pulmonary venules, which are actually tiny veins continuous with the capillaries. The venules empty into the veins, which carry blood back to the heart. Similar to the arteries, the veins usually have three layers of tissue in their walls (see Figure 1–43).

The veins differ from the arteries, however, in that the middle layer is poorly developed. As a result, the veins have thinner walls and contain less smooth muscle and less elastic tissue than the arteries. There are

FIGURE 1-43 Schematic of the components of the pulmonary blood vessels.


Non-oxygenated blood
Connective tissue
Pulmonary Artery
Arteriole
Capillaries
Elastic layers
Endothelium (Tunica intima)
Muscle layer (Tunica media)
Collagen (Tunica adventia)
Venule
Pulmonary Vein
Oxygenated blood

only two layers in the smaller veins, lacking a layer comparable to the tunica adventitia. In the systemic circulation, many medium- and large-sized veins (particularly those in the legs) contain one-way, flaplike valves that aid blood flow back to the heart. The valves open as long as the flow is toward the heart but close if flow moves away from the heart.

The veins also differ from the arteries in that they are capable of collecting a large amount of blood with very little pressure change. Because of this unique feature, the veins are called capacitance vessels. Unlike the pulmonary arteries, which generally parallel the airways, the veins move away from the bronchi and take a more direct route out of the lungs. Ultimately, the veins in each lung merge into two large veins and exit through the lung hilum. The four pulmonary veins then empty into the left atrium of the heart (see Figure 1–42).

The Lymphatic System

Lymphatic vessels are found superficially around the lungs just beneath the visceral pleura and in the dense connective tissue wrapping of the bronchioles, bronchi, pulmonary arteries, and pulmonary veins. The primary function of the lymphatic vessels is to remove excess fluid and protein molecules that leak out of the pulmonary capillaries.

Deep within the lungs, the lymphatic vessels arise from the loose space of the interstitium. The vessels follow the bronchial airways, pulmonary arteries, and veins to the hilum of the lung (Figure 1–44). Single-leaf, funnel-shaped valves are found in the lymphatic channels. These one-way valves direct fluid toward the hilum. The larger lymphatic channels are surrounded by smooth-muscle bands that actively produce peristaltic movements regulated by the autonomic nervous system. Both the smooth-muscle activity and the normal, cyclic pressure changes generated in the thoracic cavity move lymphatic fluid toward the hilum. The vessels end in the pulmonary and bronchopulmonary lymph nodes located just inside and outside the lung parenchyma (Figure 1–45).

The lymph nodes are organized collections of lymphatic tissue interspersed along the course of the lymphatic stream. Lymph nodes produce lymphocytes and monocytes. The nodes act as filters, keeping particulate matter and bacteria from entering the bloodstream.

FIGURE 1-44 Lymphatic vessels of the bronchial airways, pulmonary arteries, and veins.

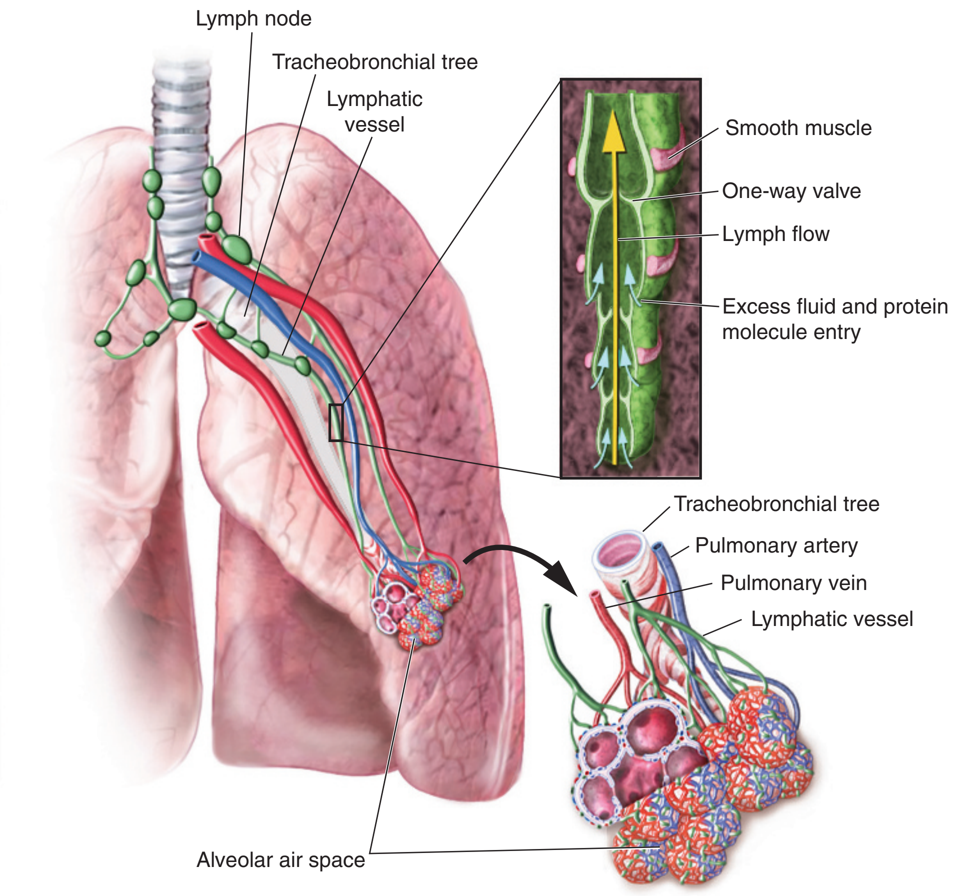
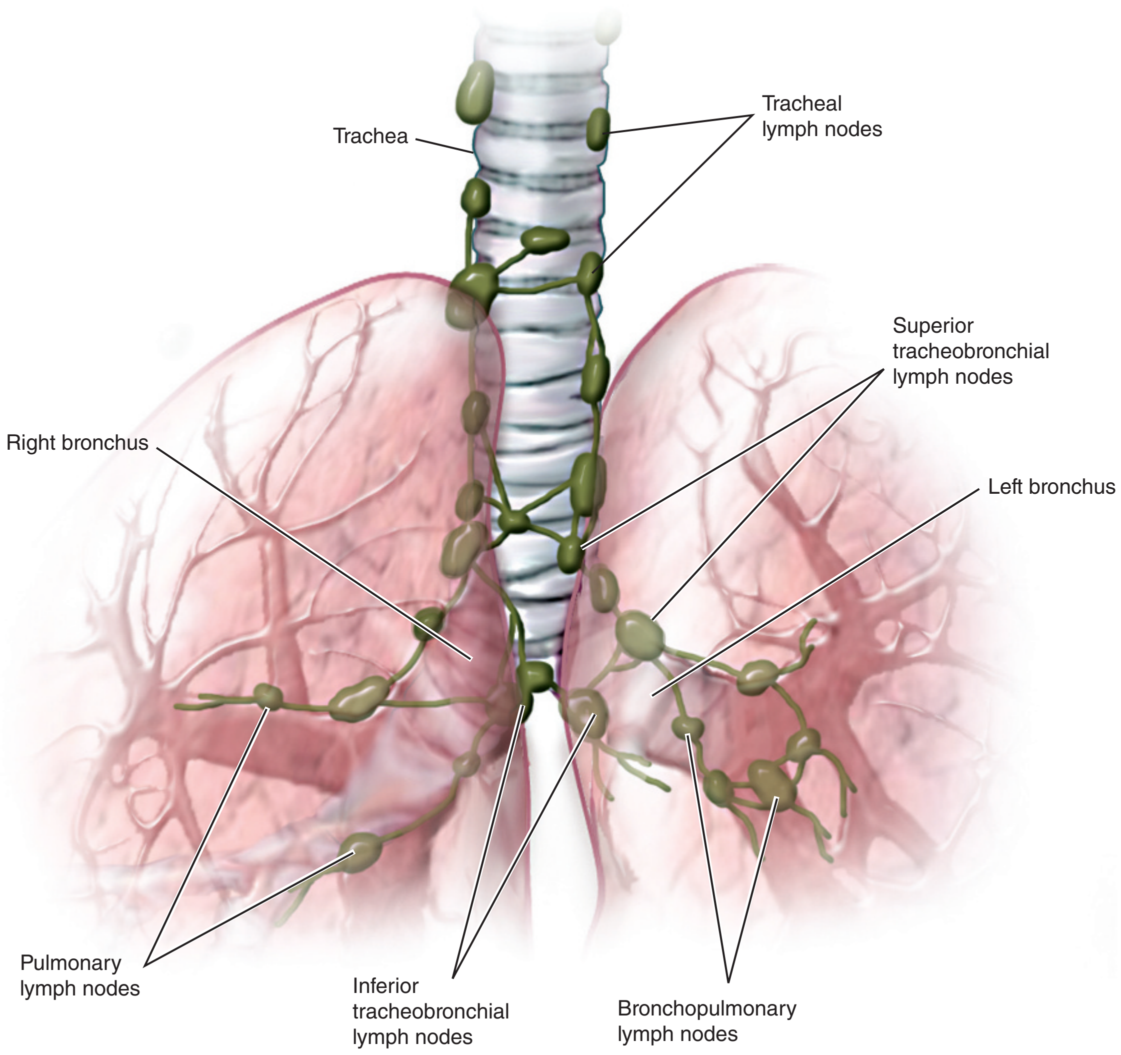

Lymph node
Tracheobronchial tree
Lymphatic vessel
Smooth muscle
One-way valve
Lymph flow
Excess fluid and protein molecule entry
Tracheobronchial tree
Pulmonary artery
Pulmonary vein
Lymphatic vessel
Alveolar air space

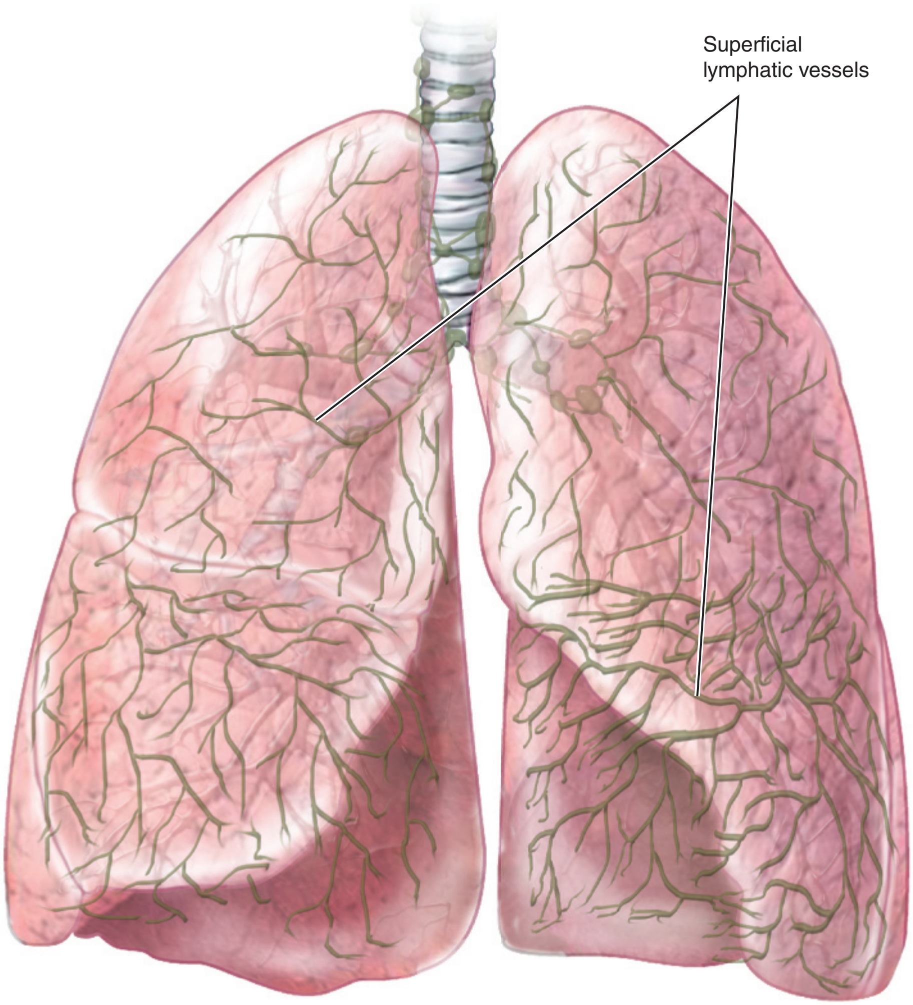
FIGURE 1-45 Lymph nodes associated with the trachea and the right and left main stem bronchi.


Trachea
Tracheal lymph nodes
Superior tracheobronchial lymph nodes
Right bronchus
Left bronchus
Pulmonary lymph nodes
Inferior tracheobronchial lymph nodes
Bronchopulmonary lymph nodes

There are no lymphatic vessels in the walls of the alveoli. Some alveoli, however, are strategically located immediately adjacent to peribronchovascular lymphatic vessels. These vessels are called juxta-alveolar lymphatics and are thought to play an active role in the removal of excess fluid and other foreign material that gain entrance into the interstitial space of the lung parenchyma. The excess fluid and foreign substances move through the thoracic duct and empty into the left brachial vein just before the superior vena cava.

There are more lymphatic vessels on the surface of the lower lung lobes than on that of the upper or middle lobes. The lymphatic channels on the left lower lobe are more numerous and larger in diameter than the lymphatic vessels on the surface of the right lower lobe (Figure 1–46). This anatomic difference provides a possible explanation why patients with bilateral effusion (i.e., the escape of fluid from the blood vessels from both lungs) commonly have more fluid in the lower right lung than in the lower left.

FIGURE 1-46 Lymphatic vessels of the visceral pleura of the lungs.



Neural Control of the Lungs

The balance, or tone, of the bronchial and arteriolar smooth muscle of the lungs is controlled by the autonomic nervous system. The autonomic nervous system is the part of the nervous system that regulates involuntary vital functions, including the activity of cardiac muscle, smooth muscle, and glands. It has two divisions: (1) the sympathetic nervous system, which accelerates the heart rate, constricts blood vessels, relaxes bronchial smooth muscles, and raises blood pressure; and (2) the parasympathetic nervous system, which slows the heart rate, constricts bronchial smooth muscles, and increases intestinal peristalsis and gland activity. Table 1–2 lists some effects of the two divisions of the autonomic nervous system.

When the sympathetic nervous system is activated, neural transmitters, such as epinephrine and norepinephrine, are released. These agents stimulate (1) the beta$_2$ receptors in the bronchial smooth muscles, causing relaxation of the airways musculature, and (2) the alpha receptors of the smooth muscles of the arterioles, causing the pulmonary vascular system to constrict. When the parasympathetic nervous system is activated, the neutral transmitter acetylcholine is released, causing constriction of the bronchial smooth muscle.

TABLE 1-2 Some Effects of Autonomic Nervous System Activity

Effector Site	Sympathetic Nervous System	Parasympathetic Nervous System
Heart	Increases rate	Decreases rate
	Increases strength of contraction	Decreases strength of contraction
Bronchial smooth muscle	Relaxation	Constriction
Bronchial glands	Decreases secretions	Increases secretions
Salivary glands	Decreases secretions	Increases secretions
Stomach	Decreases motility	Increases motility
Intestines	Decreases motility	Increases motility
Eyes	Widens pupils	Constricts pupils

Inactivity of either the sympathetic or the parasympathetic nervous system allows the action of the other to dominate the bronchial smooth-muscle response. For example, if a beta$_2$-blocking agent such as propranolol is administered to a patient, the parasympathetic nervous system becomes dominant and bronchial constriction ensues. In contrast, if a patient receives a parasympathetic blocking agent such as atropine, the sympathetic nervous system becomes dominant and bronchial relaxation occurs.

Clinical Connection 1-17

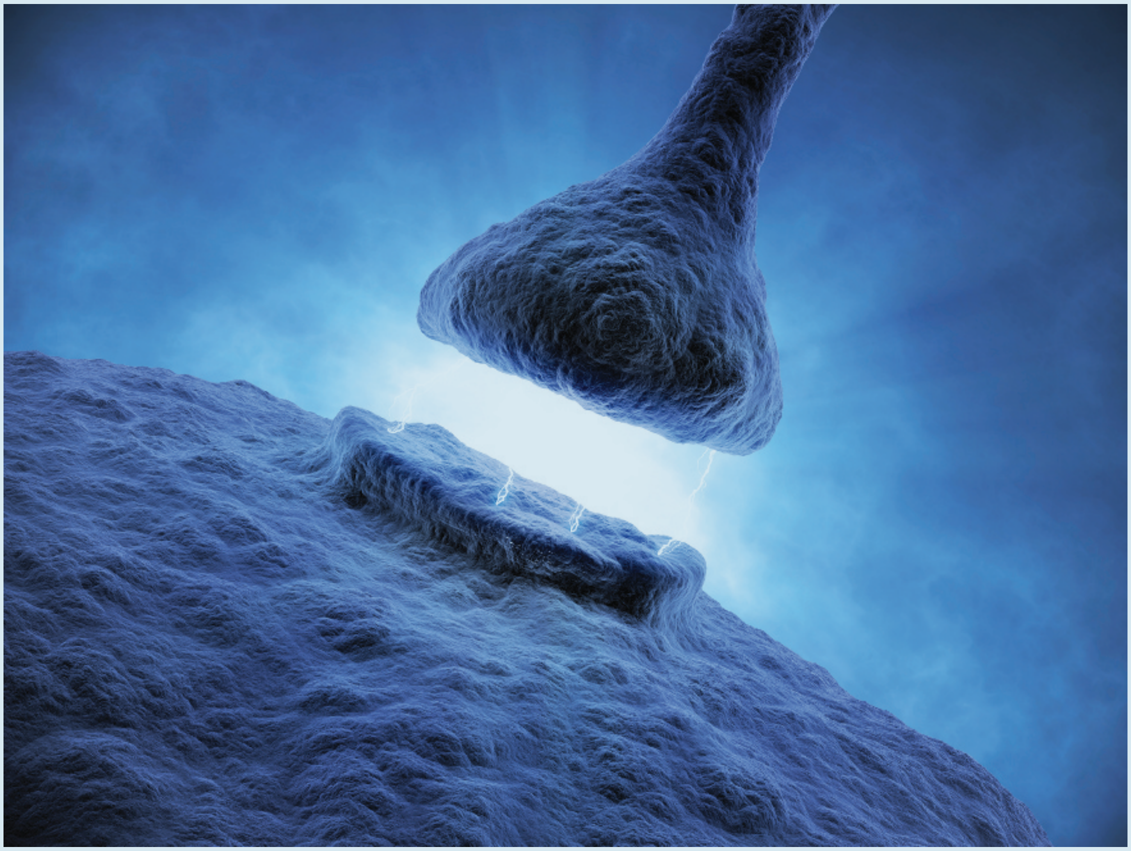
The Role of Neural Control Agents in Respiratory Care

Clinically, the respiratory therapist commonly administers inhaled aerosolized medications that mirror the bronchodilator effects of the neural receptor sites of autonomic nervous system (Figure 1–47). In general, the bronchodilator drugs used to offset bronchial smooth muscle constriction (bronchospasm) either (1) mimic the sympathetic nervous system—that is, mimic the bronchial smooth muscle relaxation effects, or (2) block the parasympathetic nervous system—that is, block the bronchial smooth muscle constriction effects. In other words, drugs that mimic the sympathetic nervous system cause bronchial smooth muscle relaxation; drugs that block the parasympathetic nervous system prevent the activation of bronchial smooth muscle constriction—thereby allowing bronchodilation to prevail.

Agents that mimic the sympathetic nervous system are called **sympathomimetic drugs**. In short, sympathomimetic agents stimulate the same **adrenergic beta$_2$ receptors**—located in the bronchial smooth muscle—that are normally stimulated by the sympathetic nervous system to cause bronchodilation. This is why sympathomimetic agents—such as **albuterol**, **levalbuterol**, **salmeterol**, and **formoterol**—are often referred to as **beta$_2$ adrenergic drugs**. On the other hand, drugs that block the **cholinergic receptors** of the parasympathetic nervous system—that is, the receptors that cause the bronchial smooth muscle constriction effect—are called **parasympatholytic agents** (also called **anticholinergic drugs**). Common aerosolized parasympatholytic agents administered by the respiratory therapist include **ipratropium bromide**. Agents that include combinations of sympathomimetic and parasympatholytic agents (e.g., ipratropium and albuterol) are also available.

Clinical Connection 1-17, Continued

FIGURE 1-47 Neural receptor synapse.



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Clinical Connection 1-18

An Asthmatic Episode and the Role of Bronchodilator and Anti-inflammatory Drugs

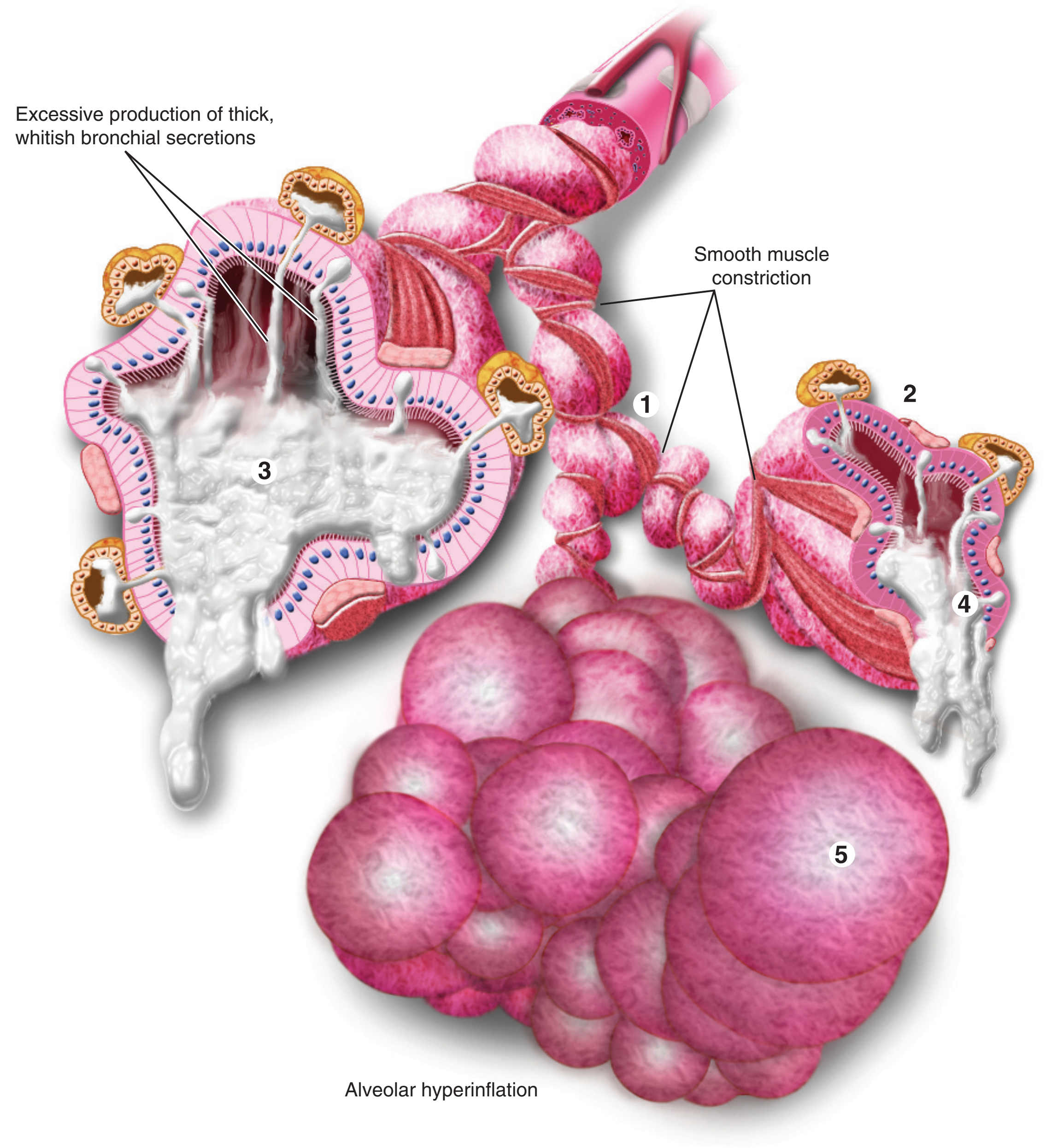
As shown in Figure 1–48, **asthma** is characterized by periodic episodes of (1) reversible bronchial smooth muscle constriction called bronchospasm; (2) airways inflammation that results in mucosal edema and airways swelling; (3) excessive production of thick, whitish bronchial secretions; (4) mucous plugging; and (5) air trapping and hyperinflation of the alveoli. The risk factors for asthma can be divided into two groups: (1) the risk factors one is born with that cause the development of asthma (e.g., genetic traits or sex), and (2) the risk factors that trigger asthma symptoms (e.g., dust, pollens, fungi, molds, animal fur, or tobacco smoke). An asthmatic episode can develop rapidly with symptoms that include a cough, wheezing, excessive mucous production, a feeling of chest tightness, and shortness of breath.

During life-threatening asthmatic attacks, fast-acting bronchodilator drugs—called **quick relief medications**—are commonly administered by the

Clinical Connection 1-18, Continued

respiratory therapist to relax constricted bronchial smooth muscles. Quick relief agents include **albuterol** or **levalbuterol**. **Controller medications** include long-acting beta agonists such as **salmeterol** or **formoterol** and anti-inflammatory corticosteroids such as **beclomethasone**, **fluticasone**, or **budesonide**. In addition, asthma management may also include agents such as **leukotriene modifiers**, **mast cell stabilizers**, **methylxanthine**, and **immunomodulators**.

FIGURE 1-48 Asthma is characterized by periodic episodes of (1) reversible bronchial smooth muscle constriction, called bronchospasm; (2) airways inflammation, which results in mucosal edema and airways swelling; (3) excessive production of thick, whitish bronchial secretions; (4) mucous plugging; and (5) air trapping and hyperinflation of the alveoli.


Excessive production of thick, whitish bronchial secretions
Smooth muscle constriction
1
2
3
4
5
Alveolar hyperinflation

The Lungs

The apex of each lung is somewhat pointed, and the base is broad and concave to accommodate the convex diaphragm (Figures 1–49 and 1–50). As shown in Figure 1–51, the apices of the lungs rise to about the level of the first rib. In the normal adult at end exhalation, the base extends anteriorly to about the level of the sixth rib (xiphoid process level) and posteriorly to about the level of the eleventh rib (two ribs below the inferior angle of the scapula). The mediastinal border of each lung is concave to fit the heart and other mediastinal structures. At the center of the mediastinal border is the hilum, where the main stem bronchi, blood vessels, lymph vessels, and various nerves enter and exit the lungs.

The right lung is larger and heavier than the left. It is divided into the upper, middle, and lower lobes by the oblique and horizontal fissures. The oblique fissure extends from the costal to the mediastinal borders of the lung and separates the upper and middle lobes from the lower lobe. The horizontal fissure extends horizontally from the oblique fissure to about the level of the fourth costal cartilage and separates the middle from the upper lobe.

The left lung is divided into only two lobes—the upper and the lower. These two lobes are separated by the oblique fissure, which extends from the costal to the mediastinal borders of the lung.

All lobes are further subdivided into bronchopulmonary segments. In Figure 1–52, the segments are numbered to demonstrate their relationship.

FIGURE 1-49 Anterior view of the lungs.

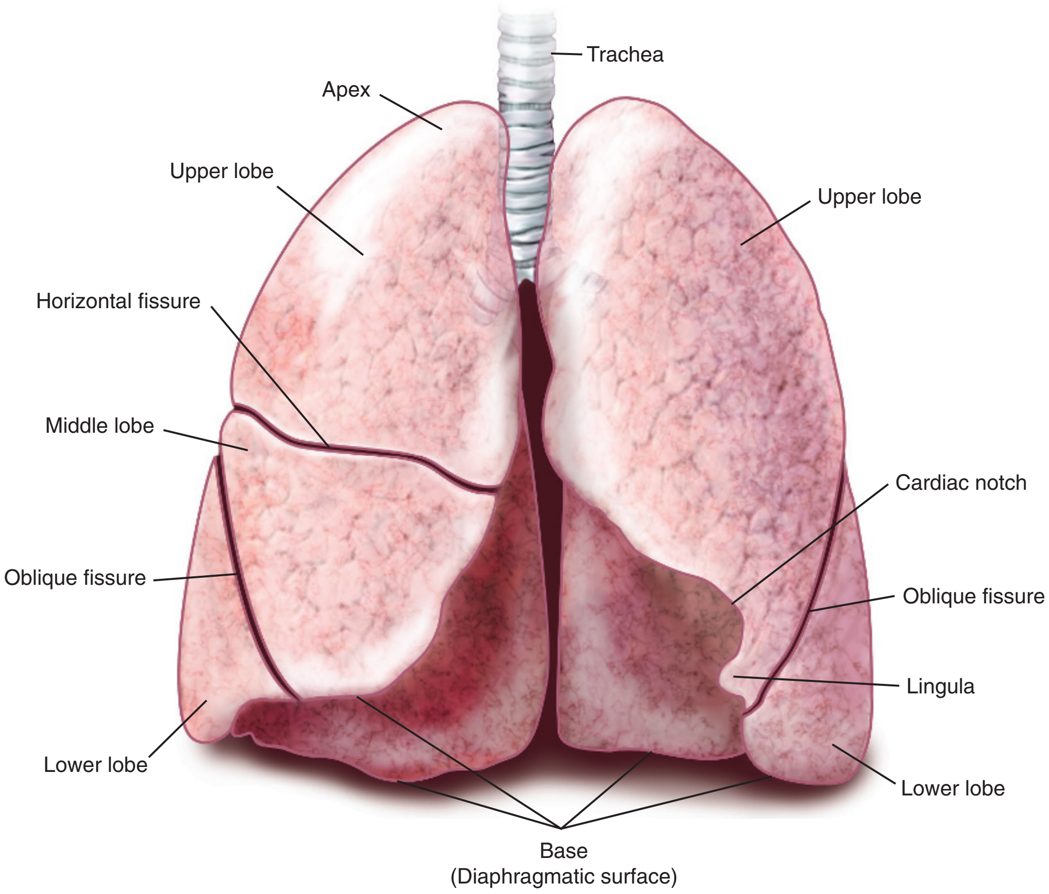


FIGURE 1-50 Medial view of the lungs.

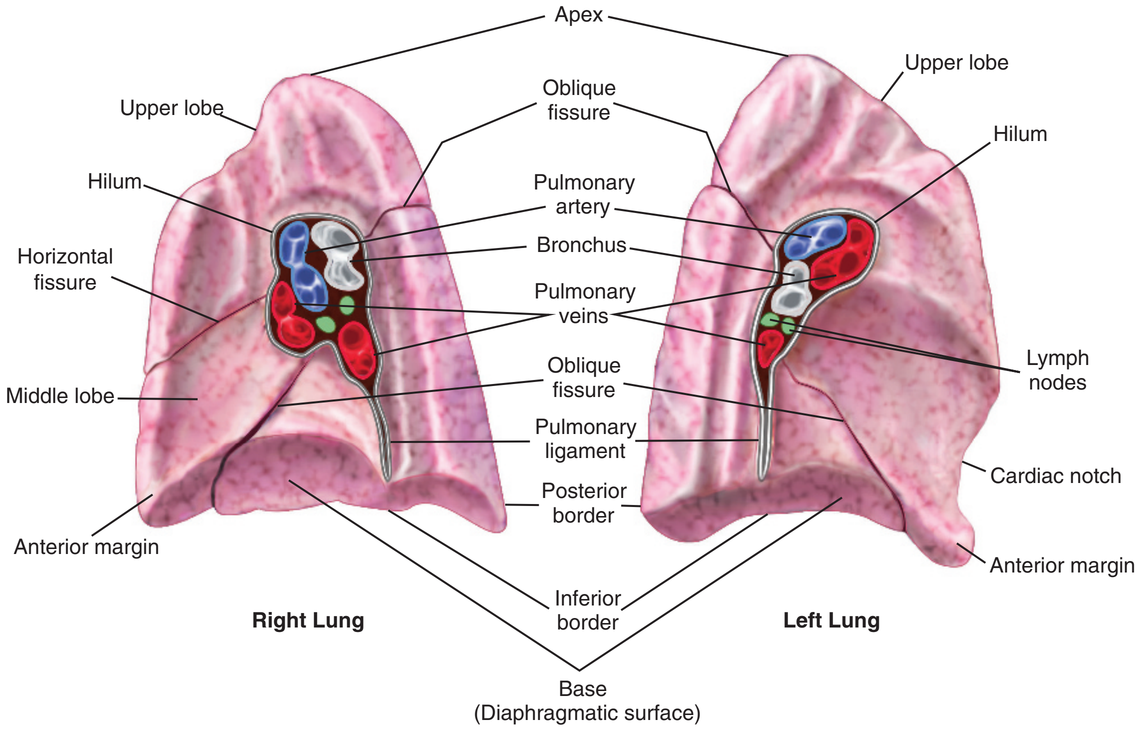

Apex
Upper lobe
Oblique fissure
Upper lobe
Hilum
Hilum
Pulmonary artery
Horizontal fissure
Bronchus
Pulmonary veins
Lymph nodes
Middle lobe
Oblique fissure
Pulmonary ligament
Cardiac notch
Posterior border
Anterior margin
Anterior margin
Inferior border
Right Lung
Left Lung
Base (Diaphragmatic surface)

FIGURE 1-51 Anatomic relationship of the lungs and the thorax.

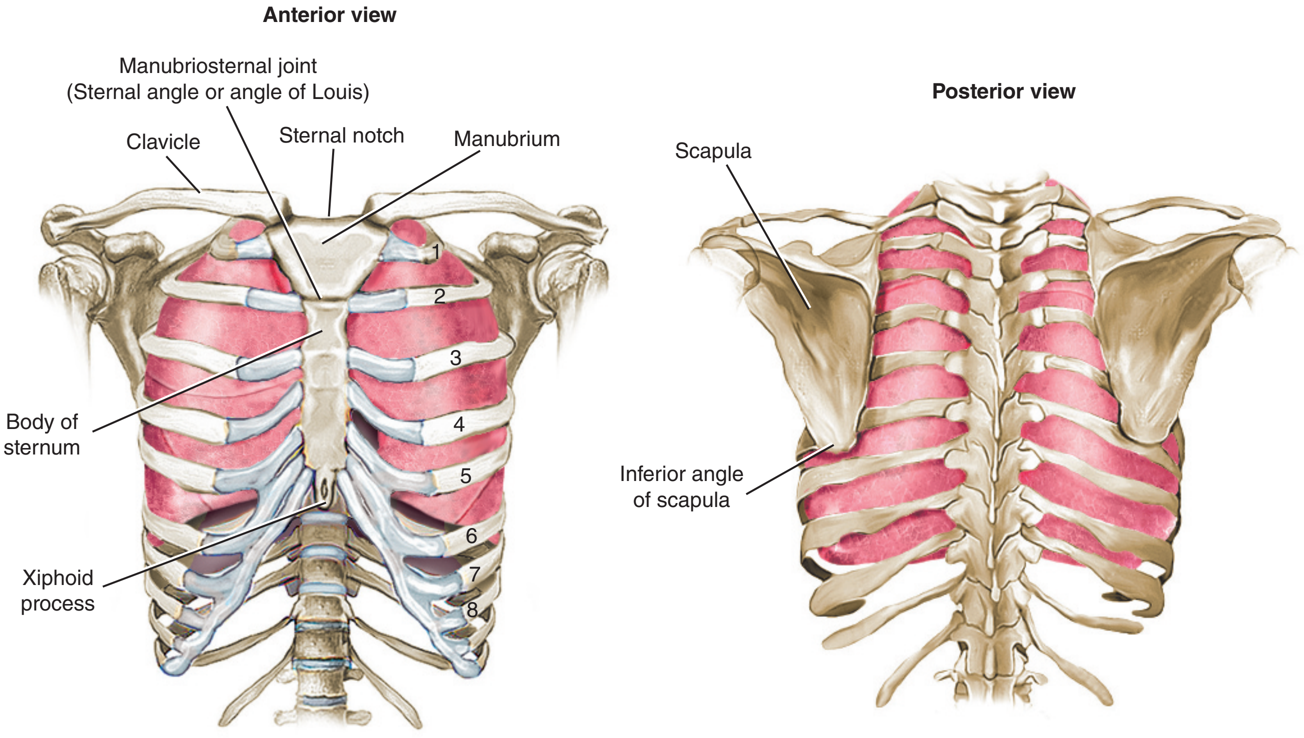
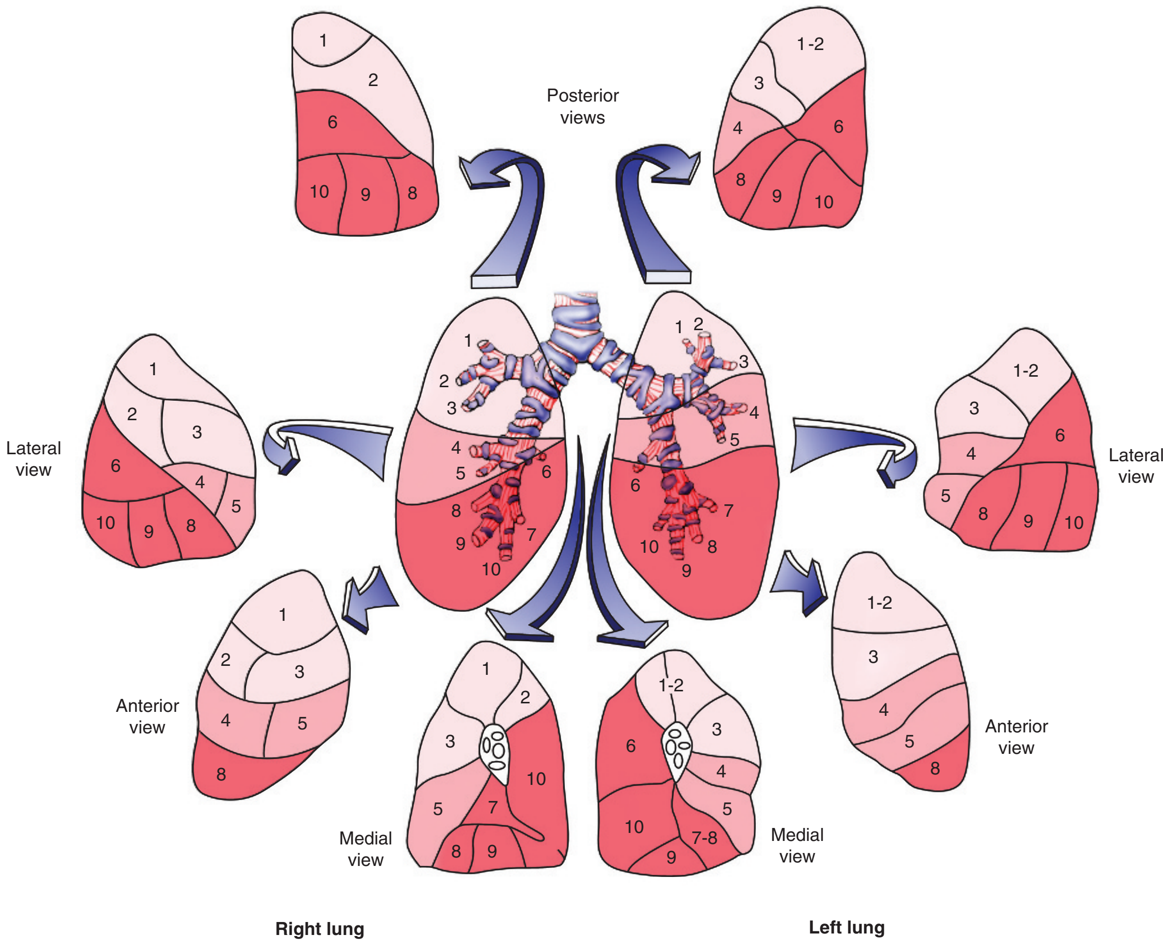

Anterior view
Manubriosternal joint (Sternal angle or angle of Louis)
Clavicle
Sternal notch
Manubrium
1
2
3
4
5
6
7
8
Body of sternum
Xiphoid process
Posterior view
Scapula
Inferior angle of scapula

FIGURE 1-52 Lung segments. Although the segment subdivisions of the right and left lungs are similar, there are some slight anatomic differences, which are noted by combined names and numbers. Because of these slight variations, some researchers consider that, technically, there are only eight segments in the left lung: the **apical posterior segments** in the upper lobe are counted as a single segment, and the **anterior medial basal segments** of the lower lobe are counted as a single segment.

Right lung		Left lung	
Upper lobe		Upper lobe	
Apical	1	Upper division	
Posterior	2	Apical/Posterior	1 & 2
Anterior	3	Anterior	3
Middle lobe		Lower division (lingular)	
Lateral	4	Superior lingula	4
Medial	5	Inferior lingula	5
Lower lobe		Lower lobe	
Superior	6	Superior	6
Medial basal	7	Anterior medial basal	7 & 8
Anterior basal	8	Lateral basal	9
Lateral basal	9	Posterior basal	10
Posterior basal	10		


Posterior views
Lateral view
Lateral view
Anterior view
Anterior view
Medial view
Medial view
Right lung
Left lung
1
2
3
4
5
6
7
8
9
10
1-2
7-8

Clinical Connection 1-19

Postural Drainage Therapy

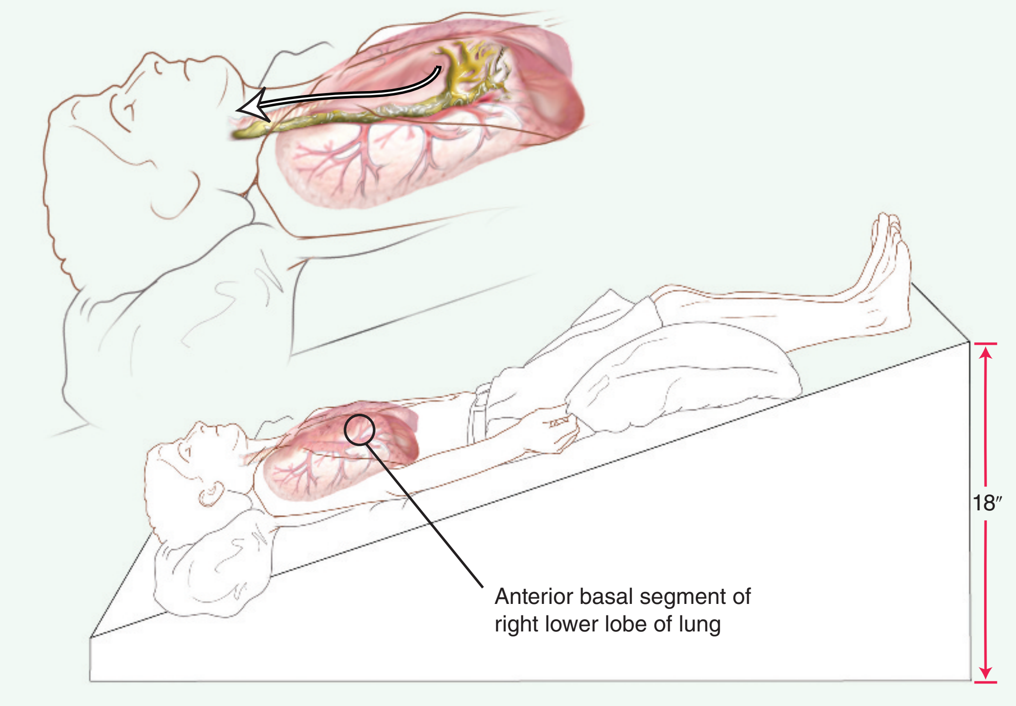
Postural drainage is commonly applied by the respiratory therapist to the patient with excessive airways secretions. Postural drainage therapy involves positioning the patient—with pillows and bed positions—to use gravity to help mobilize excessive bronchial secretions from bronchial lung segments. Depending on the specific locations and extent of the airways secretions, the patient may be placed in 1 to 12 different postural drainage positions. The indications for postural drainage therapy include patients who have (1) excessive bronchial secretions; (2) a weak or absent cough; (3) breath sounds with rhonchi (i.e., gurgling wet sounds), suggesting excessive airways secretions; and/or (4) an abnormal chest radiograph that indicates mucous plugging with alveolar collapse (atelectasis).

Clinically, the therapeutic values of postural drainage can be helpful. For example, consider the patient with both a weak cough and excessive bronchial secretions in the **anterior segment** of the **right lower lobe**. In this case—and assuming there are no contraindications for postural drainage (such as a head or neck injury or a distended abdomen)—the patient would be positioned in the supine position (lying on back) with the foot of the bed raised 18 inches. Based on the anatomy of the anterior segment of the right lower lobe, this position generates the greatest gravitational pull on the secretions located in this region of the lung (Figure 1–53).

Postural drainage is often supplemented with **percussion** and **vibration** to enhance the mobilization of secretions. Percussion and vibration entail the application of mechanical energy to the chest wall by the use of either cupped hands or a variety of electric or pneumatic devices. Once the secretions have moved into the trachea, they are either coughed out by the patient or suctioned out by the health care practitioner.

Also see Clinical Connection 1–13 (Excessive Airways Secretions) and Clinical Connection 1–14 (Abnormal Mucociliary transport Mechanism).

FIGURE 1-53 Postural drainage position for the anterior basal segment of the right lower lobe. The patient is positioned in the supine position (lying on back) with the foot of the bed elevated 18 inches.



The Mediastinum

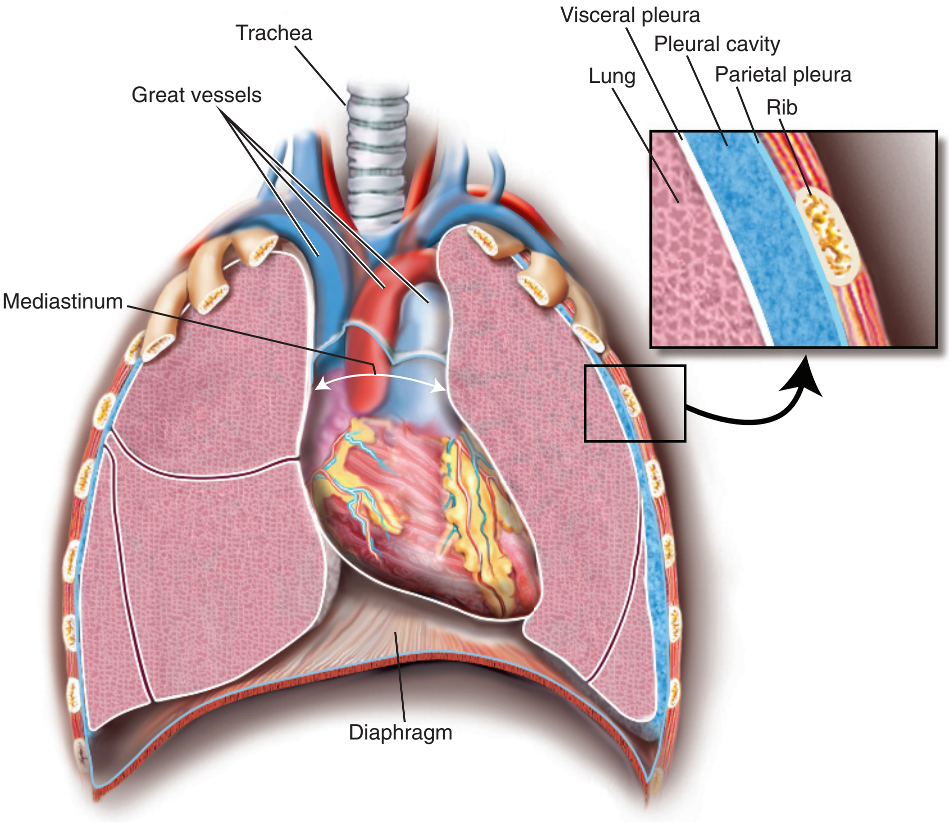
The mediastinum is a cavity that contains organs and tissues in the center of the thoracic cage between the right and left lungs (Figure 1–54). It is bordered anteriorly by the sternum and posteriorly by the thoracic vertebrae. The mediastinum contains the trachea, the heart, the major blood vessels (commonly known as the great vessels) that enter and exit the heart, various nerves, portions of the esophagus, the thymus gland, and lymph nodes. If the mediastinum is compressed or distorted, it can severely compromise the cardiopulmonary system.

The Pleural Membranes

Two moist, slick-surfaced membranes called the visceral and parietal pleurae are closely associated with the lungs. The visceral pleura is firmly attached to the outer surface of each lung and extends into each of the interlobar fissures. The parietal pleura lines the inside of the thoracic walls, the thoracic surface of the diaphragm, and the lateral portion of the mediastinum. The potential space between the visceral and parietal pleurae is called the pleural cavity (see Figure 1–54).

The visceral and parietal pleurae are held together by a thin film of serous fluid—somewhat like two flat, moistened pieces of glass. This fluid layer allows the two pleural membranes to glide over each other during inspiration and expiration. Thus, during inspiration, the pleural membranes hold the lung tissue to the

FIGURE 1-54 Major structures surrounding the lungs.



inner surface of the thorax and diaphragm, causing the lungs to expand. Because the lungs have a natural tendency to collapse and the chest wall has a natural tendency to expand, a negative or subatmospheric pressure (negative intrapleural pressure) normally exists between the parietal and visceral pleurae.

Clinical Connection 1-20

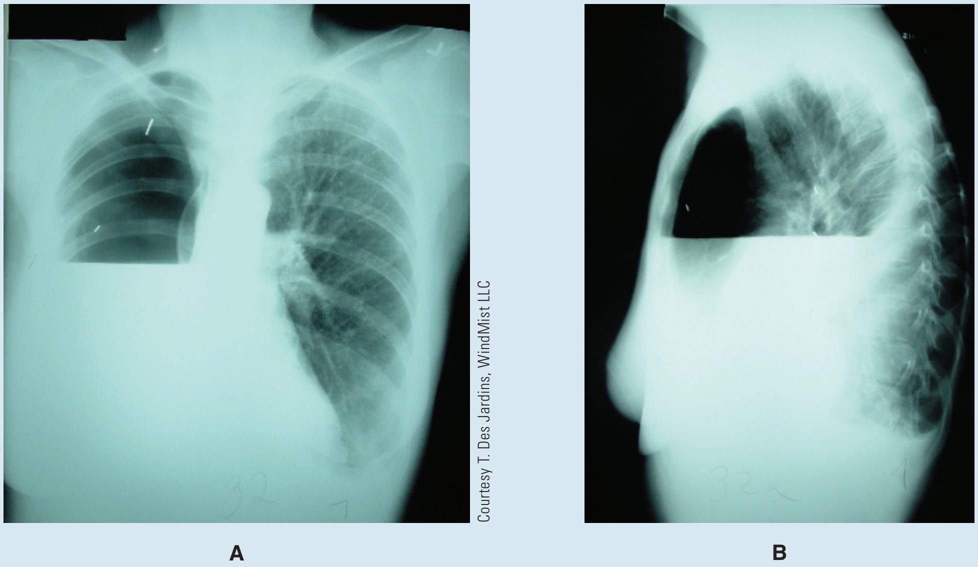
Abnormal Conditions of the Pleural Membrane

Several respiratory disorders—such as congestive heart failure, bacterial pneumonia, tuberculosis, and fungal lung diseases—can adversely affect the pleural membranes. These pulmonary disorders can cause the pleural membranes to become inflamed—a condition called **pleurisy**. The inflamed pleurae become irritated and rough. This condition causes friction and a stabbing pain with each breath—especially during inspiration. Through a stethoscope, the patient's breath sounds are described as a **friction rub**, a "leather-like" creaking or grating sound, which is caused by the roughened, inflamed surfaces of the pleura rubbing together; these sounds are evident during inspiration, expiration, or both.

In more serious cases, fluid may accumulate in the pleural cavity. The general term for fluid accumulation in the pleural cavity is **pleural effusion**, or if infected, an **empyema** (Figure 1–55). Similar to the accumulation of free air in the pleural space (see Clinical Connection 1–21: Pneumothorax), fluid accumulation separates the visceral and parietal pleura. If untreated, the lung will collapse, and the great veins may be compressed causing cardiac output to decrease. Pleural effusion and empyema cause a restrictive lung disorder.

Clinically, a pleural effusion is treated with a **thoracentesis**. A thoracentesis is a procedure in which excess fluid accumulation between the chest cavity and lungs (pleural space) is aspirated through a needle inserted through the chest wall. The fluid is examined for abnormal cells, white blood cells, red blood cells, glucose, and microorganisms. A thoracentesis is commonly performed at the bedside while the patient sits upright, with the anterior chest supported by a pillow or an over-bed table. When the patient's cardiopulmonary status is compromised—for example, because of a reoccurring fluid accumulation—the insertion of a large chest tube in the pleural space is secured for continual drainage.

FIGURE 1-55 **A.** Anterior-posterior chest X-ray of a right-sided pleural effusion. **B.** Lateral chest X-ray view of same patient.


Courtesy T. Des Jardins, WindMist LLC
Courtesy T. Des Jardins, WindMist LLC

Clinical Connection 1-21

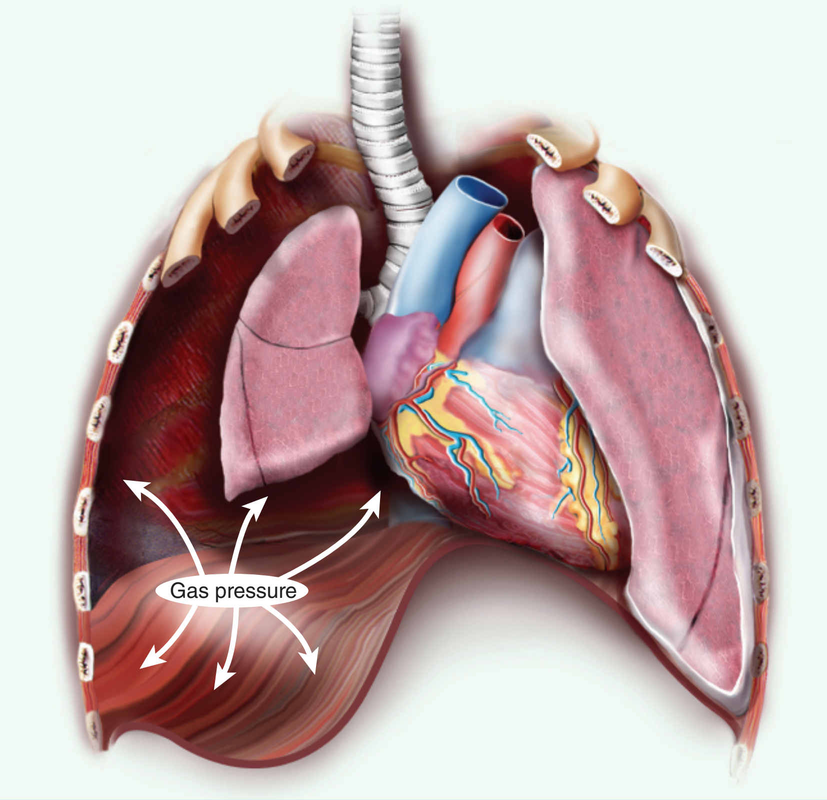
Pneumothorax

A **pneumothorax**, also known as *air in the chest cavity,* is the introduction of gas into the pleural cavity through an opening in the chest wall or a rupture of the lung. Gas accumulation in the pleural cavity causes the visceral and parietal pleural to separate and, subsequently, the lung to collapse (atelectasis). This is because when the lung's visceral and parietal pleura are separated, the **lung's natural inward recoil force** is no longer offset by the **chest wall's natural outward recoil force**—thus allowing the lung to collapse.

Common causes of a pneumothorax include (1) a penetrating chest wound (e.g., knife, bullet, or fractured rib) and (2) a rupture of the lung (commonly caused by positive pressure mechanical ventilation). A pneumothorax can be classified as either **closed** or **open**, based on the way in which gas gains entrance to the pleural space. In a **closed pneumothorax**, the gas in the intrapleural space is not in direct contact with the atmosphere (e.g., caused by rupture of the lung). In an **open pneumothorax**, the gas in the intrapleural space is in direct contact with the atmosphere and can move freely in and out (e.g., a penetrating chest wound). When the gas pressure in the intrapleural space exceeds the atmospheric pressure, the patient is said to have a **tension pneumothorax**. Figure 1–56 illustrates a right-sided tension pneumothorax.

In severe cases, the excessive gas pressure in the pleural cavity can (1) depress the diaphragm, (2) shift the mediastinum to the unaffected side of the chest, (3) compress the great veins and decrease cardiac output, and (4) diminish oxygen transport. The treatment for a pneumothorax is the insertion of a chest tube into the intrapleural space and the application of suction to draw out the air and re-expand the lung.

FIGURE 1-56 A right-side tension pneumothorax.



The Thorax

The thorax houses and protects the organs of the cardiopulmonary system. Twelve thoracic vertebrae form the posterior midline border of the thoracic cage. The sternum forms the anterior border of the chest. The sternum is composed of the manubrium sterni, the body of the sternum, and the xiphoid process. The joint between the manubrium and the body of the sternum is called the **manubriosternal joint**, and is referred to as the **sternal angle** or **angle of Louis**. Clinically, the angle of Louis provides an important palpable landmark. It identifies (1) the approximate level of the second pair of costal cartilages, (2) the level of the intervertebral disc between T4 and T5, (3) the approximate beginning and end of the aortic arch, and (4) the bifurcation of the trachea into the left and right mainstem bronchi (Figure 1–57).

The 12 pairs of ribs form the lateral boundaries of the thorax. The ribs attach directly to the vertebral column posteriorly and indirectly by way of the costal cartilage anteriorly to the sternum. The first seven ribs are referred to as true ribs, because they are attached directly to the sternum by way of their costal cartilage. Because the cartilage of the eighth, ninth, and tenth ribs attaches to the cartilage of the ribs above, they are referred to as false ribs.

Ribs 11 and 12 float freely anteriorly and are called floating ribs. There are 11 intercostal spaces between the ribs. Each intercostal space contains blood vessels, intercostal nerves, and the external and internal intercostal muscles. The veins, arteries, and nerves within each intercostal space run along the inferior margin of each rib (Figure 1–58).

FIGURE 1-57 The thorax. The angle of Louis (the joint between the manubrium and the body of the sternum) is a palpable mark of the bifurcation of the right and left mainstem bronchi.

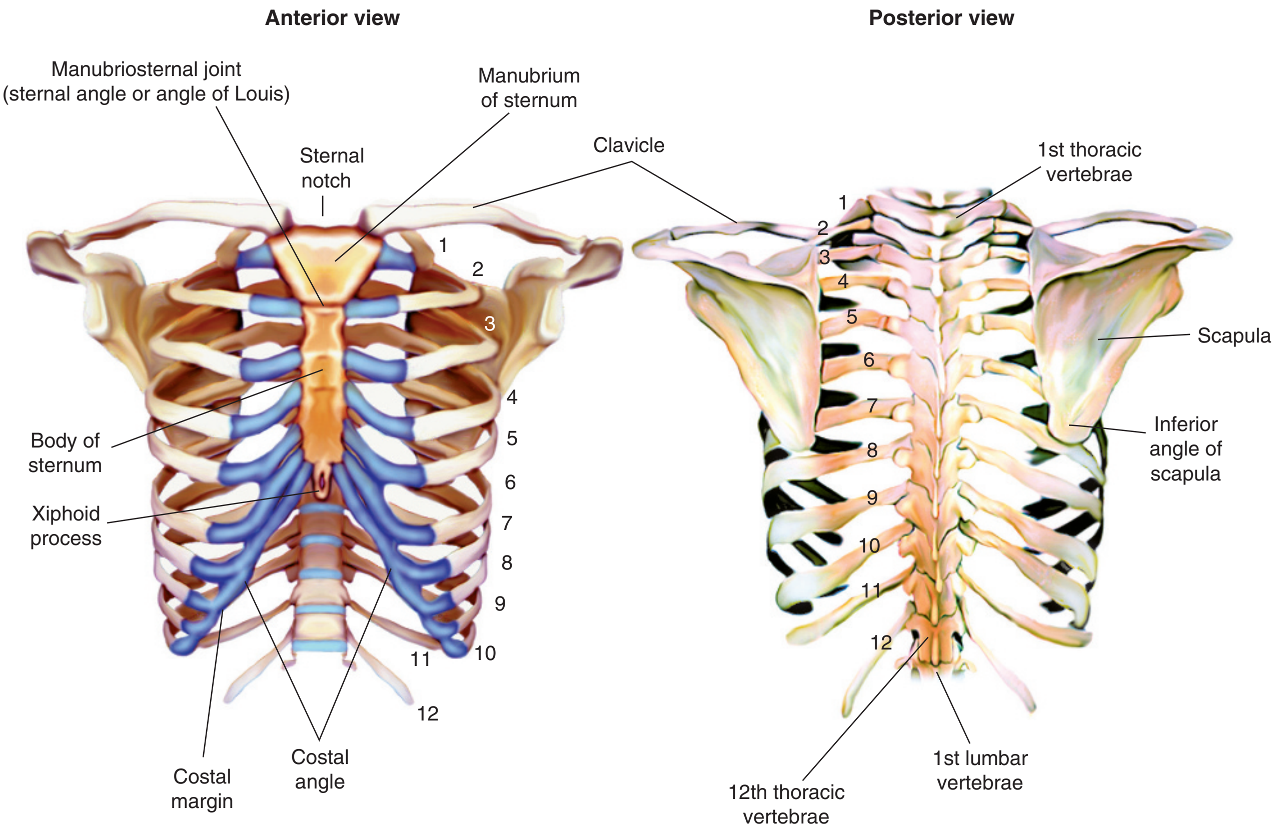
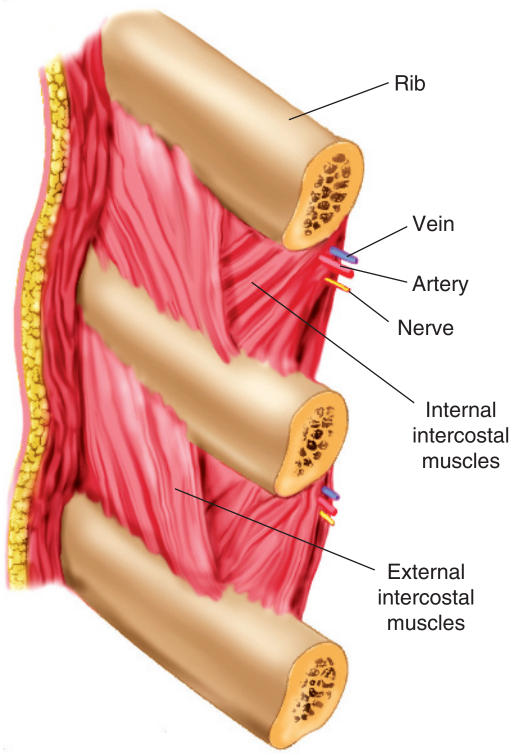

Anterior view
Posterior view
Manubriosternal joint (sternal angle or angle of Louis)
Manubrium of sternum
Sternal notch
Clavicle
1st thoracic vertebrae
Body of sternum
Xiphoid process
Costal margin
Costal angle
Scapula
Inferior angle of scapula
12th thoracic vertebrae
1st lumbar vertebrae
1
2
3
4
5
6
7
8
9
10
11
12

FIGURE 1-58 The intercostal space.

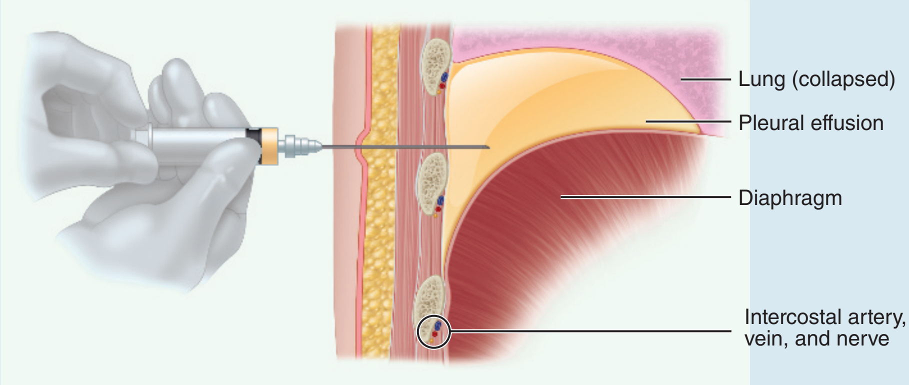

Rib
Vein
Artery
Nerve
Internal intercostal muscles
External intercostal muscles

Clinical Connection 1-22

Puncture Site for a Thoracentesis

Because the intercostal veins, arteries, and nerves course along the lower margin of each rib, the protocol for a thoracentesis entails the insertion of the needle slightly superior to the rib margin (Figure 1–59). Although bleeding from a thoracentesis is rare, a needle puncture is one of the most common causes of an **iatrogenic pneumothorax**—that is, a health complication caused by medical personnel or procedure.

FIGURE 1-59 To safely miss the intercostal artery, vein, and nerve, a thoracentesis involves the insertion of the needle slightly superior to the rib margin.


Lung (collapsed)
Pleural effusion
Diaphragm
Intercostal artery, vein, and nerve

The Muscles of Ventilation

During normal quiet breathing, contraction of the **diaphragm** alone, or contraction of both the diaphragm and **external intercostal muscles**, activate quiet inspiration. The diaphragm is the major muscle of ventilation (Figure 1–60). It is a dome-shaped musculofibrous partition located between the thoracic cavity and the abdominal cavity. Although the diaphragm is generally referred to as one muscle, it is actually composed of two separate muscles known as the right and left hemidiaphragms.

Each hemidiaphragm arises from the lumbar vertebrae, the costal margin, and the xiphoid process. The two muscles then merge at the midline into a broad connective sheet called the central tendon. The diaphragm is pierced by the esophagus, the aorta, several nerves, and the inferior vena cava. Terminal branches of the phrenic nerves, which leave the spinal cord between the third and fifth cervical segments (C3, C4, and C5), supply the primary motor innervation to each hemidiaphragm. The lower thoracic nerves also contribute to the motor innervation of each hemidiaphragm.

When stimulated to contract, the diaphragm moves downward—making the thoracic cavity longer—and the lower ribs move upward and outward. This action increases the volume of the thoracic cavity, which, in turn, lowers the intrapleural and intra-alveolar pressures in the thoracic cavity. As a result, gas from the atmosphere flows into the lungs. During expiration, the diaphragm relaxes and moves

FIGURE 1–60 The diaphragm.

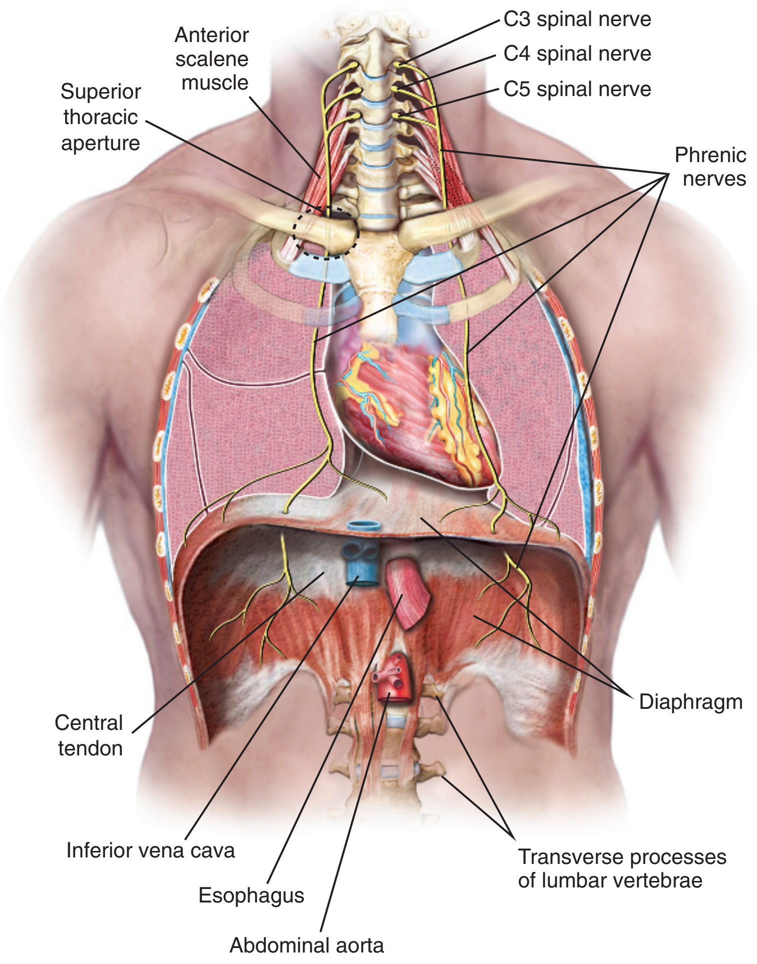
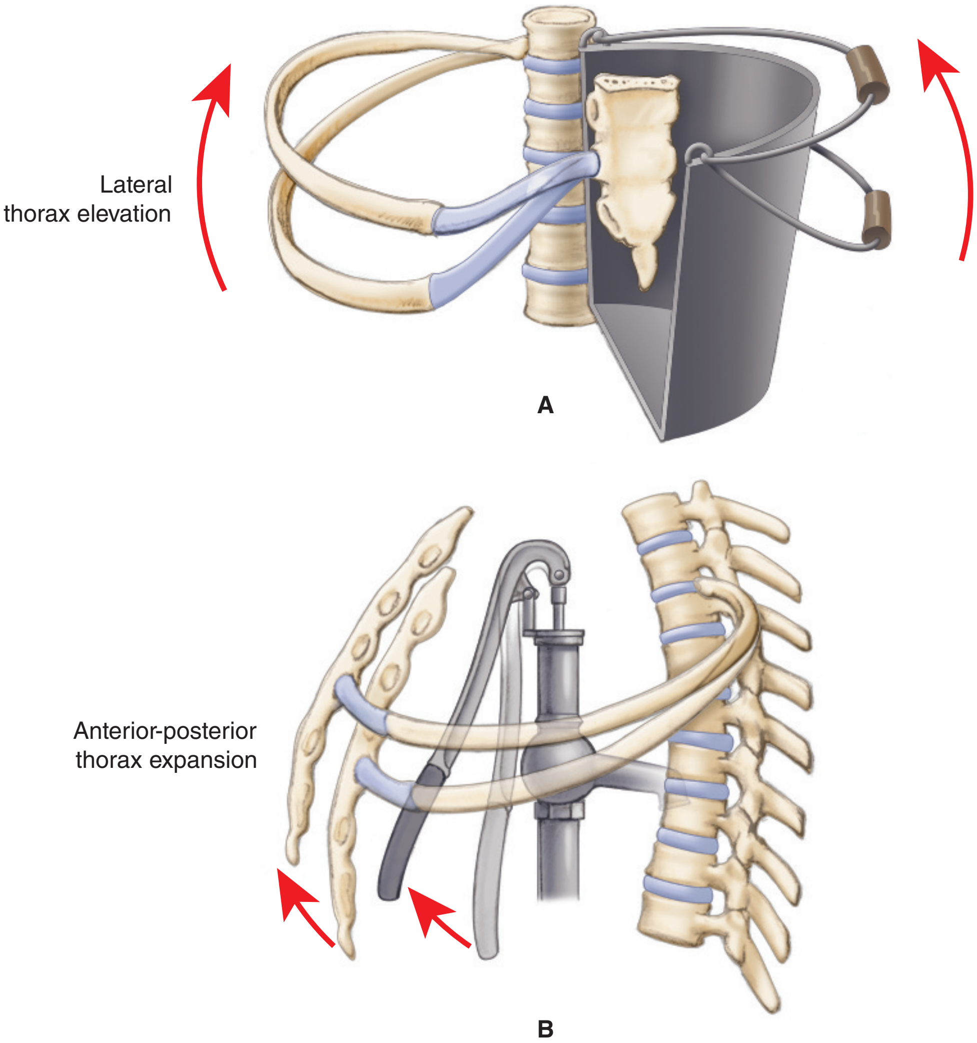

Anterior scalene muscle
Superior thoracic aperture
C3 spinal nerve
C4 spinal nerve
C5 spinal nerve
Phrenic nerves
Diaphragm
Central tendon
Inferior vena cava
Esophagus
Abdominal aorta
Transverse processes of lumbar vertebrae

FIGURE 1-61 The movement of the rib cage during breathing. **A.** "Bucket-handle" motion. **B.** "Pump-handle" motion.



upward—making the thoracic cavity smaller. This action increases the intrapleural and intra-alveolar pressures, causing gas to flow out of the lungs.

The external intercostal muscles also work during inspiration to elevate the lateral portion of the thoracic cavity in what is called the "bucket-handle" motion (Figure 1–61A). At the same time, the sternum moves upward, causing the anterior-posterior portion of the thorax to increase in what is called the "pump-handle" motion (Figure 1-61B).

Finally, during periods of respiratory distress, the contractions of the accessory muscles of inspiration—the scalenus, sternocleidomastoid, pectoralis major, and trapezius muscles—are typically activated to aid in the elevation of the sternum and rib cage during inspiration.

The Accessory Muscles of Ventilation

During normal ventilation by a healthy person, the diaphragm alone can manage the task of moving gas in and out of the lungs. However, during vigorous exercise and the advanced stages of COPD, the accessory muscles of inspiration and expiration are activated to assist the diaphragm.

The Accessory Muscles of Inspiration

The accessory muscles of inspiration are those muscles that are recruited to assist the diaphragm in creating a subatmospheric pressure in the lungs to enable adequate inspiration. The major accessory muscles of inspiration are:

- External intercostal muscles
- Scalenus muscles
- Sternocleidomastoid muscles
- Pectoralis major muscles
- Trapezius muscles

External Intercostal Muscles

The external intercostal muscles arise from the lower border of each rib (the upper limit of an intercostal space) and insert into the upper border of the rib below. Anteriorly, the fibers run downward and medially. Posteriorly, the fibers run downward and laterally (Figure 1–62). The external intercostal muscles contract during inspiration and pull the ribs upward and outward, increasing both the lateral and anteroposterior diameter of the thorax (an antagonistic action to the internal intercostal muscles). This action increases lung volume and prevents retraction of the intercostal space during an excessively forceful inspiration.

Scalenus Muscles

The scalenus muscles are three separate muscles that function as a unit. They are known as the anterior, the medial, and the posterior scalene muscles. They originate on the transverse processes of the second to the sixth cervical vertebrae and insert into the first and second ribs (Figure 1–63).

FIGURE 1-62 Internal and external intercostal muscles.

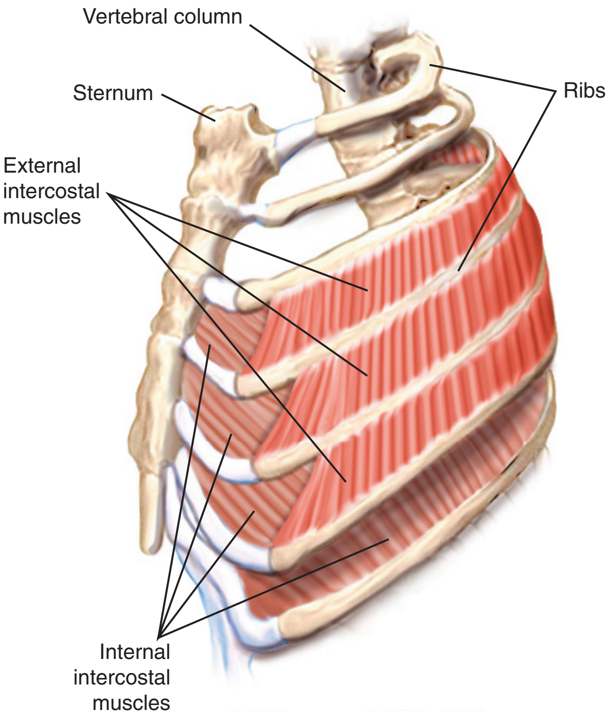
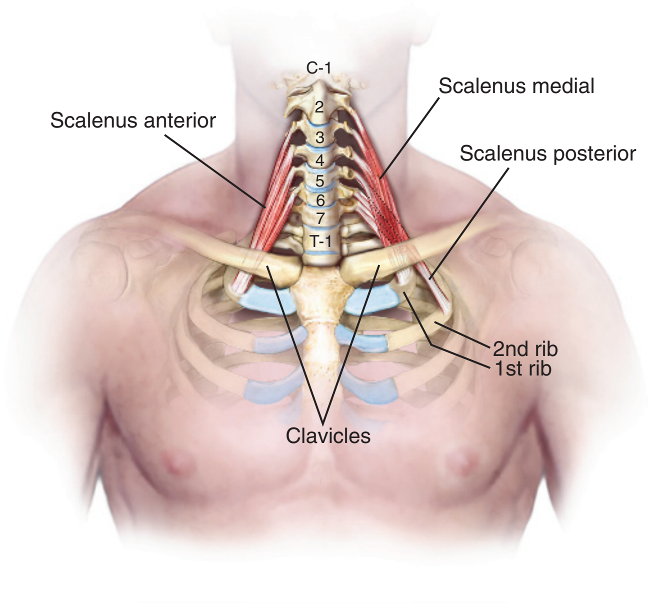


FIGURE 1–63 Scalenus muscles.



The primary function of these muscles is to flex the neck. When used as accessory muscles for inspiration, they elevate the first and second ribs, an action that decreases the intrapleural pressure.

Sternocleidomastoid Muscles

The sternocleidomastoid muscles are located on each side of the neck (Figure 1–64). They originate from the sternum and the clavicle and insert into the mastoid process and occipital bone of the skull. Normally, the sternocleidomastoid muscles pull from their sternoclavicular origin and rotate the head to the opposite side and turn it upward. When the sternocleidomastoid muscles function as an accessory muscle of inspiration, the head and neck are fixed by other muscles and the sternocleidomastoid pulls from its insertion on the skull and elevates the sternum. This action increases the anteroposterior diameter of the chest.

Pectoralis Major Muscles

The pectoralis major muscles are powerful, fan-shaped muscles located on each side of the upper chest. They originate from the clavicle and the sternum and insert into the upper part of the humerus.

Normally, the pectoralis majors pull from their sternoclavicular origin and bring the upper arm to the body in a hugging motion (Figure 1–65). When functioning as accessory muscles of inspiration, they pull from the humeral insertion and elevate the chest, resulting in an increased anteroposterior diameter. Patients with COPD frequently brace their arms against something stationary and use their pectoralis majors to increase the diameter of their chest (Figure 1–66).

Trapezius Muscles

The trapezius muscles are large, flat, triangular muscles that are situated superficially in the upper back and the back of the neck. They originate from the occipital bone, the ligamentum nuchae, and the spinous processes of the seventh cervical vertebra and all the thoracic vertebrae. They insert into the spine of the scapula, the acromion process, and the lateral third of the clavicle (Figure 1–67).

FIGURE 1-64 Sternocleidomastoid muscles.

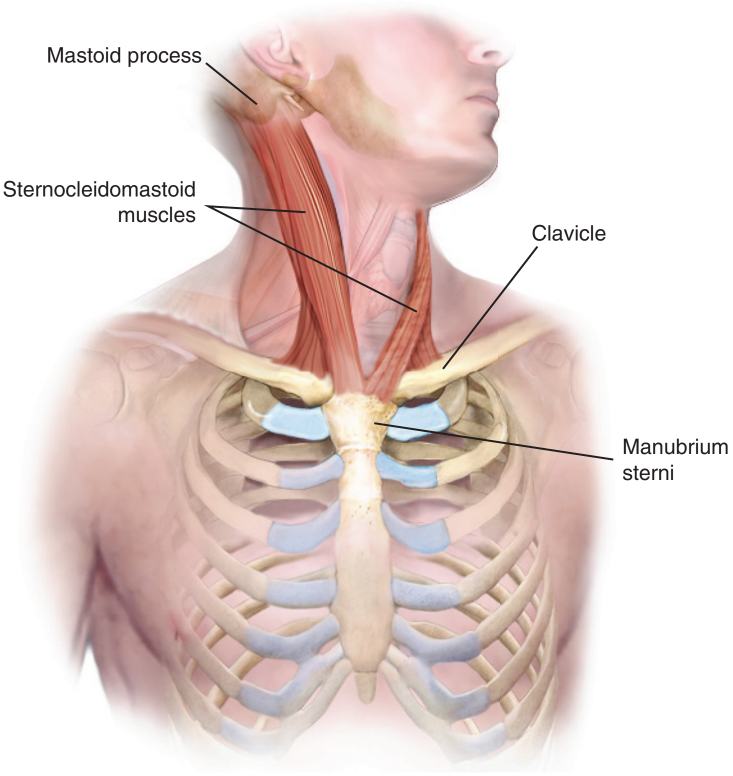

Mastoid process
Sternocleidomastoid muscles
Clavicle
Manubrium sterni

FIGURE 1-65 Pectoralis major muscles.

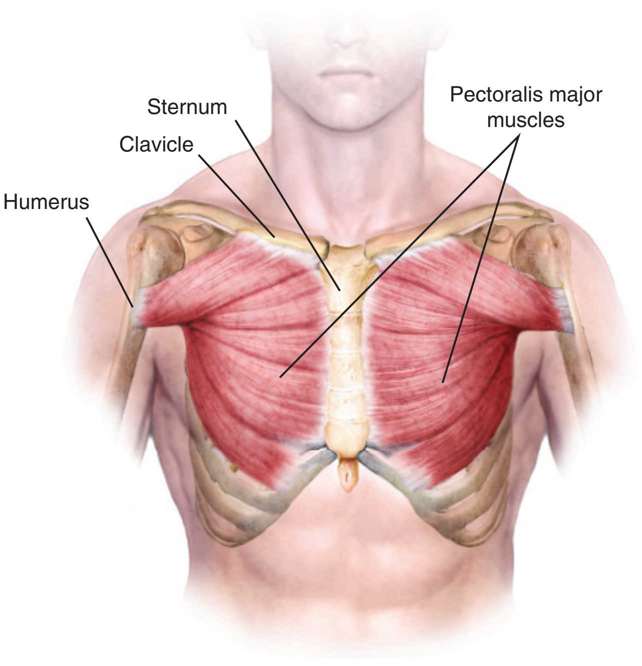

Sternum
Pectoralis major muscles
Clavicle
Humerus

FIGURE 1-66 How an individual may appear when using the pectoralis major muscles for inspiration.

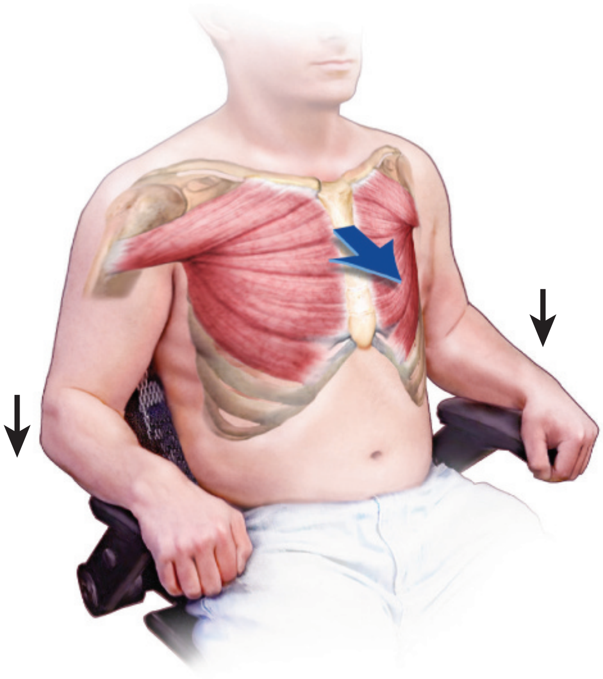


FIGURE 1-67 Trapezius muscles.

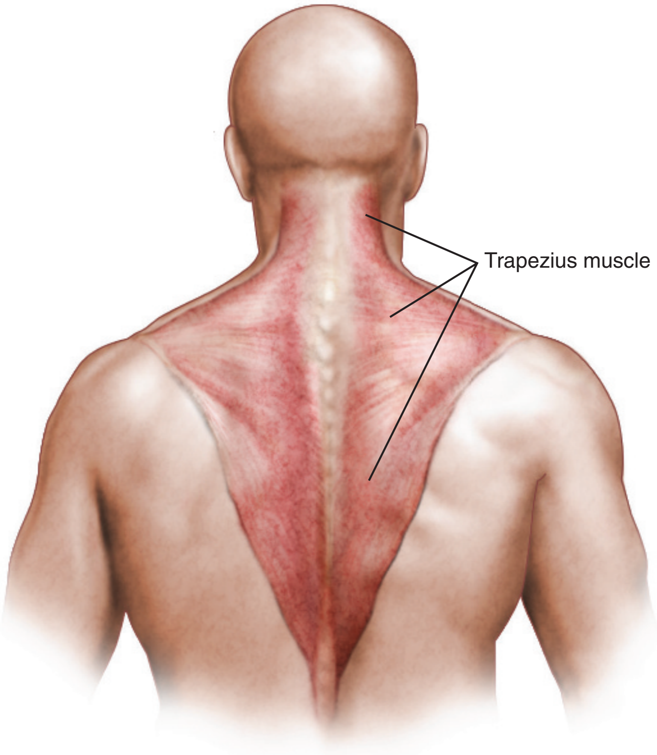
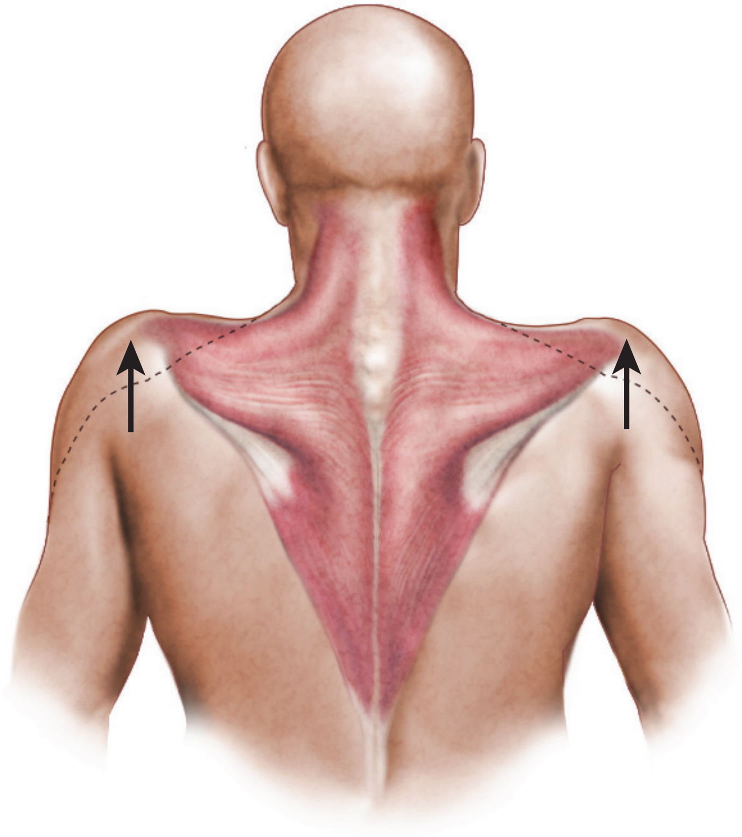


FIGURE 1-68 Shrugging of the shoulders typifies the action of the trapezius muscles.



Normally, the trapezius muscles rotate the scapula, raise the shoulders, and abduct and flex the arms. Their action is typified in shrugging of the shoulders (Figure 1–68). When used as accessory muscles of inspiration, the trapezius muscles help to elevate the thoracic cage.

The Accessory Muscles of Expiration

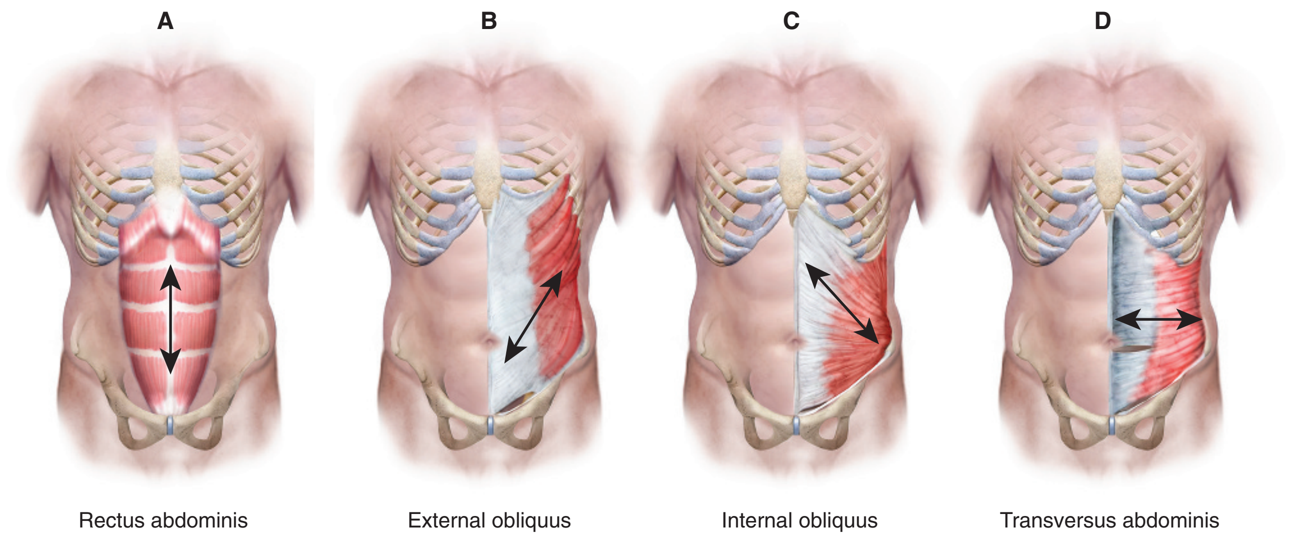
The accessory muscles of expiration are the muscles recruited to assist in exhalation when airways resistance becomes significantly elevated. When these muscles contract, they increase the intrapleural pressure and offset the increased airways resistance. The major accessory muscles of exhalation are:

- Rectus abdominis muscles
- External abdominis obliquus muscles
- Internal abdominis obliquus muscles
- Transversus abdominis muscles
- Internal intercostal muscles

Rectus Abdominis Muscles

The rectus abdominis muscles are a pair of muscles that extend the entire length of the abdomen. Each muscle forms a vertical mass about 10 cm wide and is separated from the other by the linea alba. The muscles

FIGURE 1-69 Accessory muscles of expiration.



arise from the iliac crest and pubic symphysis and insert into the xiphoid process and the fifth, sixth, and seventh ribs.

When contracted, the rectus abdominis muscles assist in compressing the abdominal contents. This compression, in turn, pushes the diaphragm into the thoracic cage (Figure 1–69A), thereby assisting in exhalation.

External Abdominis Obliquus Muscles

The external abdominis obliquus muscles are broad, thin muscles located on the anterolateral sides of the abdomen. They are the longest and the most superficial of all the anterolateral abdominal muscles. They arise by eight digitations from the lower eight ribs and the abdominal aponeurosis and insert into the iliac crest and the linea alba.

When contracted, the external abdominis obliquus muscles assist in compressing the abdominal contents, which, in turn, push the diaphragm into the thoracic cage (Figure 1–69B), thereby assisting in exhalation.

Internal Abdominis Obliquus Muscles

Smaller and thinner than the external abdominis obliquus, the internal abdominis obliquus muscles are located in the lateral and ventral parts of the abdominal wall directly under the external abdominis obliquus muscles. They arise from the inguinal ligament, the iliac crest, and the lower portion of the lumbar aponeurosis. They insert into the last four ribs and into the linea alba.

The internal abdominis obliquus muscles also assist in exhalation by compressing the abdominal contents and in pushing the diaphragm into the thoracic cage (Figure 1–69C).

Transversus Abdominis Muscles

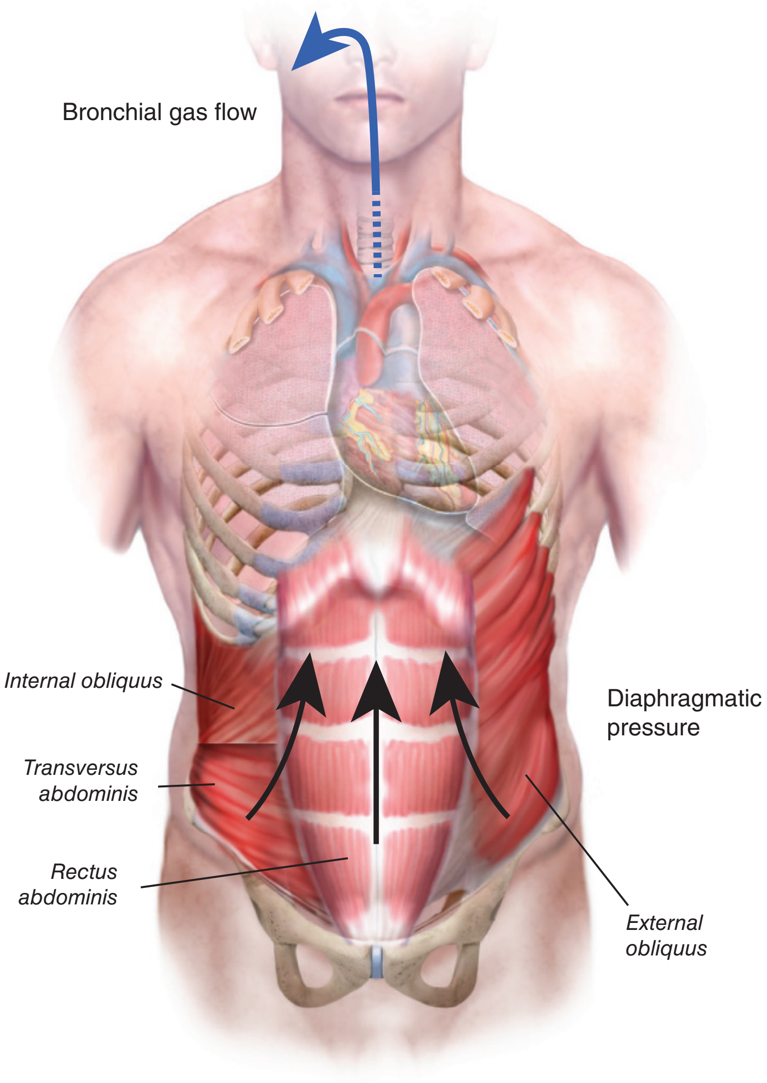
The transversus abdominis muscles are found immediately under the internal abdominis obliquus muscles. These muscles arise from the inguinal ligament, the iliac crest, the thoracolumbar fascia, and the lower six ribs and insert into the linea alba. When activated, they also help to constrict the abdominal contents (Figure 1–69D).

When all four pairs of accessory muscles of exhalation contract, the abdominal pressure increases and drives the diaphragm into the thoracic cage. As the diaphragm moves into the thoracic cage during exhalation, the intrapleural pressure increases, thereby enhancing the amount of gas flow (Figure 1–70).

Internal Intercostal Muscles

The internal intercostal muscles run between the ribs immediately beneath the external intercostal muscles. The muscles arise from the inferior border of each rib and insert into the superior border of the rib below. Anteriorly, the fibers run in a downward and lateral direction. Posteriorly, the fibers run downward and in a medial direction (see Figure 1–62). The internal intercostal muscles contract during expiration and pull the ribs downward and inward, decreasing both the lateral and anteroposterior diameter of the thorax (an antagonistic action to the external intercostal muscles). This action decreases lung volume and offsets intercostal bulging during excessive expiration.

FIGURE 1-70 The collective action of the accessory muscles of expiration causes the intrapleural pressure to increase, the chest to move outward, and bronchial gas flow to increase.



Chapter Summary

An essential cornerstone to the understanding of the practice of respiratory care is a strong knowledge base of the normal anatomy and physiology of the respiratory system. The major anatomic areas of the respiratory system can be divided into (1) the upper airways, (2) the lower airways, (3) the sites of gas exchange, (4) the pulmonary vascular system, (5) the lymphatic system, (6) the neural control of the lungs, (7) the lungs, (8) the mediastinum, (9) the pleural membranes, (10) the thorax, (11) the muscles of ventilation, and (12) the accessory muscles of ventilation. The upper airways include the structures and functions associated with the nose, oral cavity, nasal pharynx, oropharynx, laryngopharynx, and larynx. The lower airways include the structures and functions related to the tracheobronchial tree and its histology.

The anatomic structures associated with sites of gas exchange include the respiratory bronchioles, alveolar ducts, alveolar sacs, and the primary lobules. The alveolar epithelium consists of type I cells, type II cells, pulmonary surfactant, pores of Kohn, alveolar macrophages, and the interstitium. The structures of the pulmonary vascular system include the arteries, arterioles, capillaries, venules, and veins. The components of the lymphatic system include the lymph nodes and juxta-alveolar lymphatics. The neural control of the lungs consists of the autonomic nervous system, sympathetic nervous system, and parasympathetic nervous system. Clinical connections associated with the neural control of the lung include the role of neural control agents in respiratory care, an asthmatic episode, and the role of bronchodilator and anti-inflammatory drugs.

The key structures of the lung include the apex, base, mediastinal border, hilum, right lung (upper, middle, and lower lobes), left lung (upper and lower lobes), and the lung segments. A clinical connection associated with the lung segments includes the therapeutic effects of postural drainage therapy. Anatomic structures of the mediastinum are the trachea, heart, major blood vessels, nerves, esophagus, thymus gland, and lymph nodes. Anatomic components of the pleural membranes are the parietal pleura, visceral pleura, and pleural cavity. Clinical connections associated with the pleural membranes include pleurisy, friction rub, pleural effusion, empyema, thoracentesis, and pneumothorax.

The major parts of the thorax include the thoracic vertebrae, sternum, manubrium sterni, xyphoid process, true ribs, false ribs, and floating ribs. A clinical connection associated with the ribs of the thorax includes the puncture site for a thoracentesis. The major structures related to the diaphragm are the right and left hemidiaphragms, the central tendon, the phrenic nerve, and the lower thoracic nerves. The accessory muscles of ventilation are the external intercostal muscles, scalene muscles, sternocleidomastoid muscles, pectoralis major muscles, and trapezius muscles. The accessory muscles of expiration are the rectus abdominis muscles, external abdominis obliquus muscles, internal abdominis obliquus muscles, and the internal intercostal muscles.

Clinical connections associated with these topics include (1) nasal flaring and alar collapse, (2) the nose—a route of administration for topical agents, (3) nosebleed (epistaxis), (4) nasal congestion and its influence on taste, (5) rhinitis, (6) sinusitis, (7) nasal polyps, (8) infected and swollen pharyngeal tonsils (adenoids), (9) otitis media, (10) endotracheal tubes, (11) laryngitis, (12) croup syndrome, (13) excessive airways secretions, (14) abnormal mucociliary transport mechanism, (15) hazards associated with endotracheal tubes, (16) inadvertent intubation of right main stem bronchus, (17) the role of neural control agents in respiratory care, (18) an asthmatic episode and the role of bronchodilator and anti-inflammatory drugs, (19) postural drainage therapy, (20) abnormal conditions of the pleural membrane, (21) pneumothorax, and (22) puncture site for a thoracentesis.

For the respiratory therapist, a strong foundation of the normal anatomy and physiology of the respiratory system is an essential prerequisite to better understand the anatomic alterations of the lungs caused by specific respiratory disorders, the pathophysiologic mechanisms activated throughout the respiratory system as a result of the anatomic alterations, the clinical manifestations that develop as a result of the pathophysiologic mechanisms, and the basic respiratory therapies used to improve the anatomic alterations and pathophysiologic mechanisms caused by the disease. When the anatomic alterations and pathophysiologic mechanisms caused by the disorder are improved, the clinical manifestations also should improve.

Review Questions

1. Which of the following lines the anterior one-third of the nasal cavity?

A. Stratified squamous epithelium
B. Simple cuboidal epithelium
C. Pseudostratified ciliated columnar epithelium
D. Simple squamous epithelium

2. Which of the following form(s) the nasal septum?

1. Frontal process of the maxilla bone
2. Ethmoid bone
3. Nasal bones
4. Vomer
   A. 3 only
   B. 4 only
   C. 1 and 3 only
   D. 2 and 4 only

3. Which of the following prevents the aspiration of foods and liquids?

A. Epiglottis
B. Cricoid cartilage
C. Arytenoid cartilages
D. Thyroid cartilages

4. The canals of Lambert are found in the

A. trachea.
B. terminal bronchioles.
C. alveoli.
D. main stem bronchi.

5. The pharyngotympanic (auditory) tubes are found in the

A. nasopharynx.
B. oropharynx.
C. laryngopharynx.
D. oral cavity.

6. The inferior portion of the larynx is composed of the

A. thyroid cartilage.
B. hyoid bone.
C. glottis.
D. cricoid cartilage.

7. Which of the following has the greatest combined cross-sectional area?

A. Terminal bronchioles
B. Lobar bronchi
C. Trachea
D. Segmental bronchi

8. The left main stem bronchus angles off from the carina at about

A. 10–20 degrees from the carina.
B. 20–30 degrees from the carina.
C. 30–40 degrees from the carina.
D. 40–60 degrees from the carina.

9. Ninety-five percent of the alveolar surface is composed of which of the following?

1. Type I cells
2. Granular pneumocytes
3. Type II cells
4. Squamous pneumocytes
   A. 1 only
   B. 2 only
   C. 2 and 3 only
   D. 1 and 4 only

10. Which of the following is (are) released when the parasympathetic nerve fibers are stimulated?

1. Norepinephrine
2. Atropine
3. Epinephrine
4. Acetylcholine
   A. 2 only
   B. 4 only
   C. 1 and 3 only
   D. 1, 2, and 3 only

11. Which of the following is (are) released when the sympathetic nerve fibers are stimulated?

1. Norepinephrine
2. Propranolol
3. Acetylcholine
4. Epinephrine
   A. 1 only
   B. 2 only
   C. 1 and 4 only
   D. 2, 3, and 4 only

12. Pseudostratified ciliated columnar epithelium lines which of the following?

1. Oropharynx
2. Trachea
3. Nasopharynx
4. Oral cavity
5. Laryngopharynx
   A. 2 only
   B. 1 and 4 only

    C. 2 and 3 only
    D. 1, 2, 3, and 5 only

13. Which of the following is (are) accessory muscles of inspiration?

1. Trapezius muscles
2. Internal abdominis obliquus muscles
3. Scalene muscles
4. Transversus abdominis muscles
    A. 1 only
    B. 2 only
    C. 1 and 3 only
    D. 2 and 4 only

14. The horizontal fissure separates the

A. middle and upper lobes of the right lung.
B. upper and lower lobes of the left lung.
C. middle and lower lobes of the right lung.
D. oblique fissure of the left lung.

15. Which of the following supplies (supply) the motor innervation of each hemidiaphragm?

1. Vagus nerve (tenth cranial nerve)
2. Phrenic nerve
3. Lower thoracic nerves
4. Glossopharyngeal nerve (ninth cranial nerve)
    A. 1 only
    B. 2 only
    C. 1 and 4 only
    D. 2 and 3 only

16. The lung segment called the superior lingula is found in the

A. left lung, lower division of the upper lobe.
B. right lung, lower lobe.
C. left lung, upper division of the upper lobe.
D. right lung, upper lobe.

17. Cartilage is found in which of the following structures of the tracheobronchial tree?

1. Bronchioles
2. Respiratory bronchioles
3. Segmental bronchi
4. Terminal bronchioles
    A. 1 only
    B. 3 only
    C. 2 and 3 only
    D. 1 and 4 only

18. The bronchial arteries nourish the tracheobronchial tree down to, and including, which of the following?

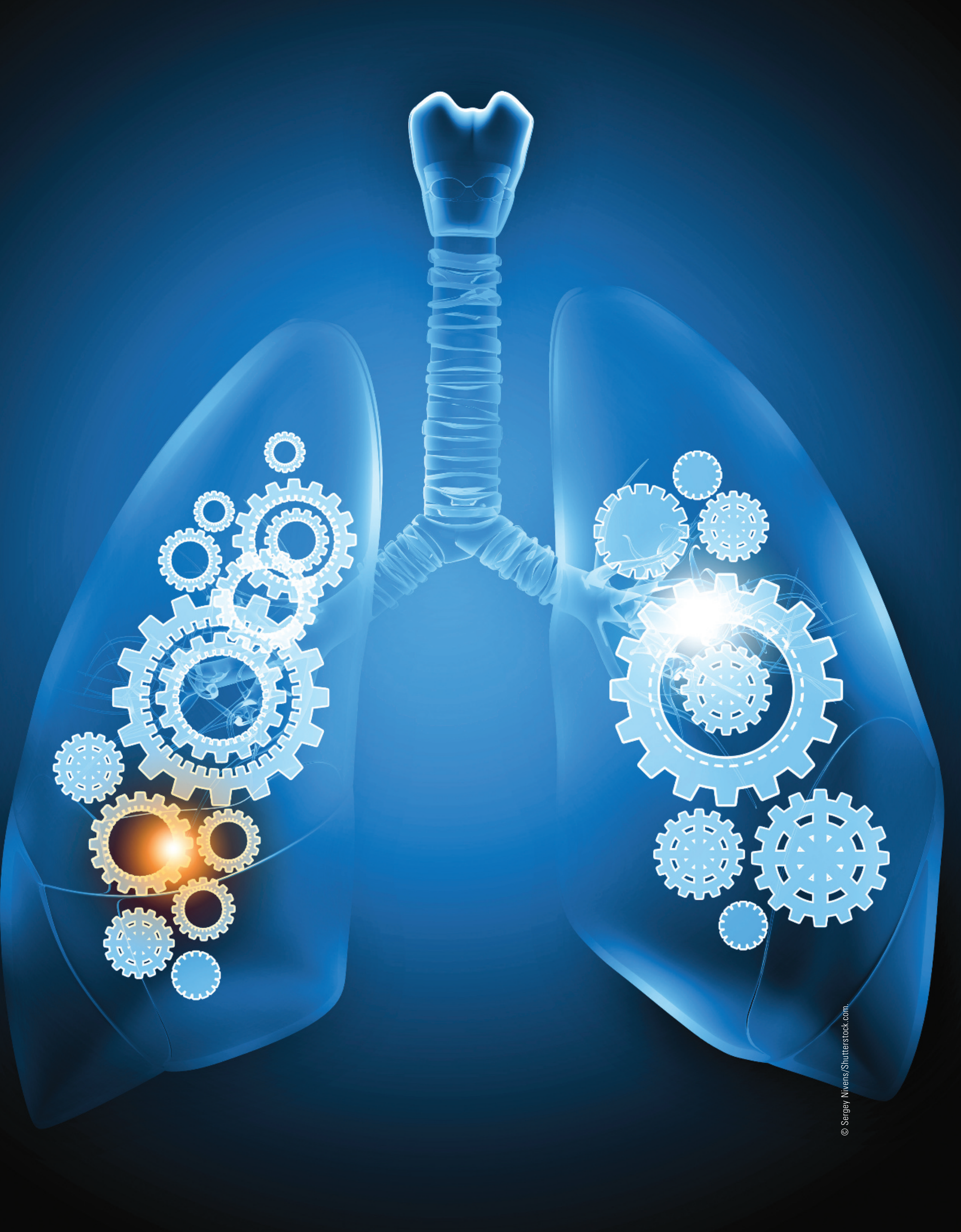
A. Respiratory bronchioles
B. Segmental bronchi
C. Terminal bronchioles
D. Subsegmental bronchi

19. Which of the following elevates the soft palate?

A. Palatoglossal muscle
B. Levator veli palatine muscle
C. Mylohyoid muscles
D. Palatopharyngeal muscle

20. Which of the following are called the resistance vessels?

A. Arterioles
B. Veins
C. Venules
D. Arteries



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CHAPTER 2

Ventilation

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Define ventilation.
2. Explain the role of the atmospheric pressure, pressure gradients, and Boyle's law on pulmonary ventilation.
3. Differentiate between the following pressure gradients across the lungs: driving pressure, transrespiratory pressure, transmural pressure, transpulmonary pressure, and transthoracic pressure.
4. Describe how the primary mechanisms of ventilation are applied to the human airways, and include the excursion of the diaphragm and the effects on pleural pressure, intra-alveolar pressure, and bronchial gas flow during
    - Inspiration.
    - End-inspiration.
    - Expiration.
    - End-expiration.
5. Describe the elastic properties of the lung and chest wall.
6. Define lung compliance.
7. Calculate lung compliance.
8. List respiratory disorders that cause a deficiency of pulmonary surfactant.
9. Describe how Poiseuille's law arranged for flow and Poiseuille's law arranged for pressure relate to the radius of the bronchial airways.
10. Define airway resistance and explain how it relates to laminar flow, turbulent flow, and tracheobronchial or transitional flow.
11. Calculate airway resistance.
12. Define time constants and explain how they relate to alveolar units.
13. Explain the meaning of dynamic compliance.
14. Differentiate between alveolar ventilation and dead space ventilation.
15. Describe how the depth and rate of breathing affect alveolar ventilation.
16. Calculate an individual's alveolar ventilation when given the following information: alveolar ventilation, dead space ventilation, and breaths per minute.
17. Describe how the normal pleural pressure differences cause regional differences in normal lung ventilation.
18. Describe how the decreased lung compliance and increased airway resistance alter the ventilatory pattern.
19. Describe breathing conditions frequently seen by respiratory care therapists in clinical settings.

Introduction

The term **ventilation** is defined as the process that moves gases between the external environment and the alveoli. It is the mechanism by which oxygen is carried from the atmosphere to the alveoli and by which carbon dioxide (delivered to the lungs in mixed venous blood) is carried from the alveoli to the atmosphere.

To fully understand the process of ventilation, the respiratory therapist must understand (1) the **mechanisms of pulmonary ventilation**, (2) the **elastic properties of the lungs and chest wall**, (3) the **dynamic characteristics of the lungs** and **how they affect ventilation**, and (4) the **characteristics of normal and abnormal ventilatory patterns**.

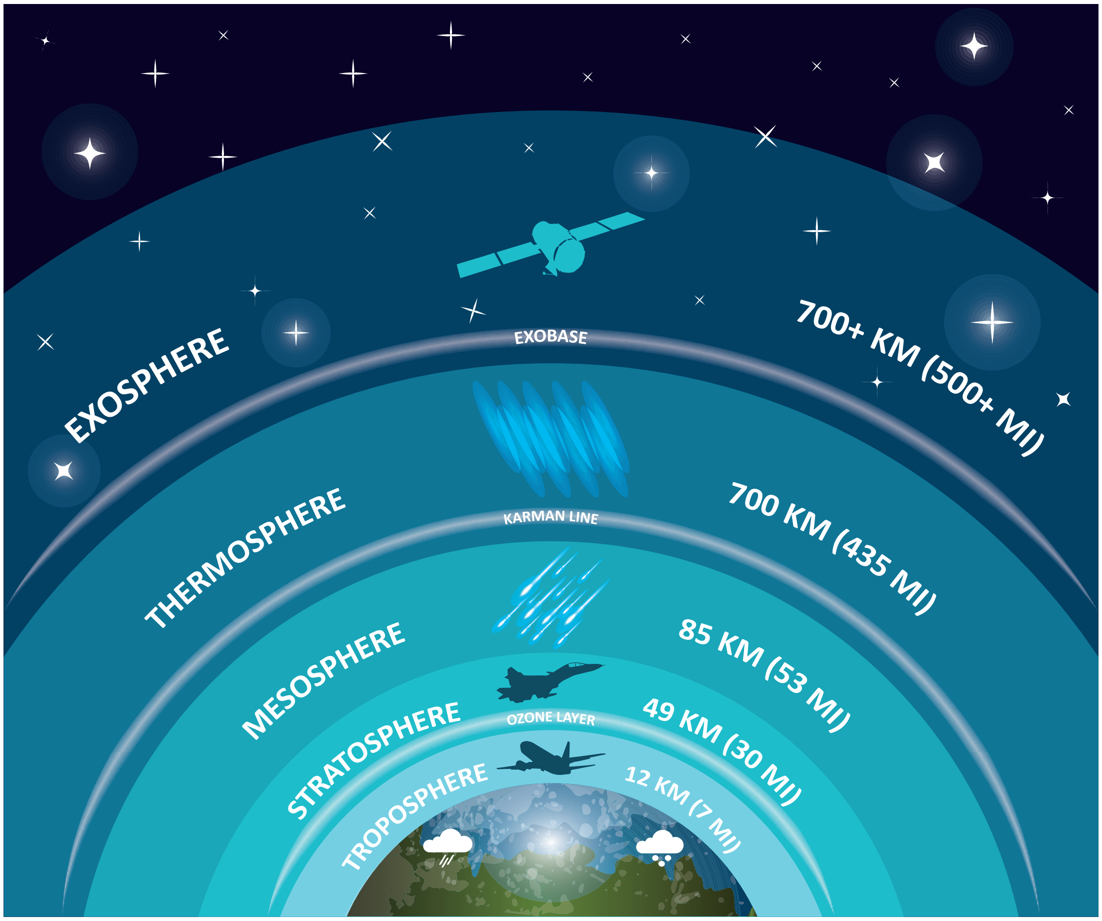
Mechanisms of Pulmonary Ventilation

Before the primary mechanisms of pulmonary ventilation can be described, it is important to have a solid understanding of the composition and function of the (1) atmospheric gases, (2) atmospheric pressures, and (3) measuring units used to quantify the atmospheric pressure.

The Atmospheric Gases

As shown in Figure 2–1, the Earth's atmospheric gases are subdivided into the following five layers: troposphere, stratosphere, mesosphere, thermosphere, and exosphere. These five different atmospheric gas layers are based on temperature. The atmospheric gases are composed of nitrogen (78.08%), oxygen (20.95%), carbon dioxide (0.03%), and some trace amounts such as argon (0.93%). All of these atmospheric gases are

FIGURE 2–1 Layers of the atmosphere.


EXOSPHERE
EXOBASE
700+ KM (500+ MI)
THERMOSPHERE
KARMAN LINE
700 KM (435 MI)
MESOSPHERE
85 KM (53 MI)
STRATOSPHERE
OZONE LAYER
49 KM (30 MI)
TROPOSPHERE
12 KM (7 MI)

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held in place by the force—that is, the pull—of Earth's gravity. Without this gravitational pull of the gases toward the Earth's surface, the air molecules would quickly spread out into space (Figure 2–2).

The Atmospheric Pressures

Because of the relative weight of the gas molecules throughout the atmosphere, the gases exert a force called the **atmospheric pressure (P_{atm})**—also called **the barometric pressure (P_B)**. The P_B is defined as the force per unit area exerted at any given point throughout the atmosphere by the weight of the air above this location. Normally, the pressure inside the human body is approximately equal to the pressure that surrounds the body—thus, preventing the body from being crushed.

The fundamental bases for the P_B force is analogous to the pressure (i.e., the force) generated at different locations in a column of water. For example, as shown in Figure 2–3, the "weight" of water in a column of water progressively decreases from the bottom to the top of the water column. Thus, the pressure—that is, the force—generated at any given point in the water column also progressively decreases from

FIGURE 2-2 Atmospheric gases and their respective percentages. The black arrows represent the gravitational pull holding the atmospheric gases in place.

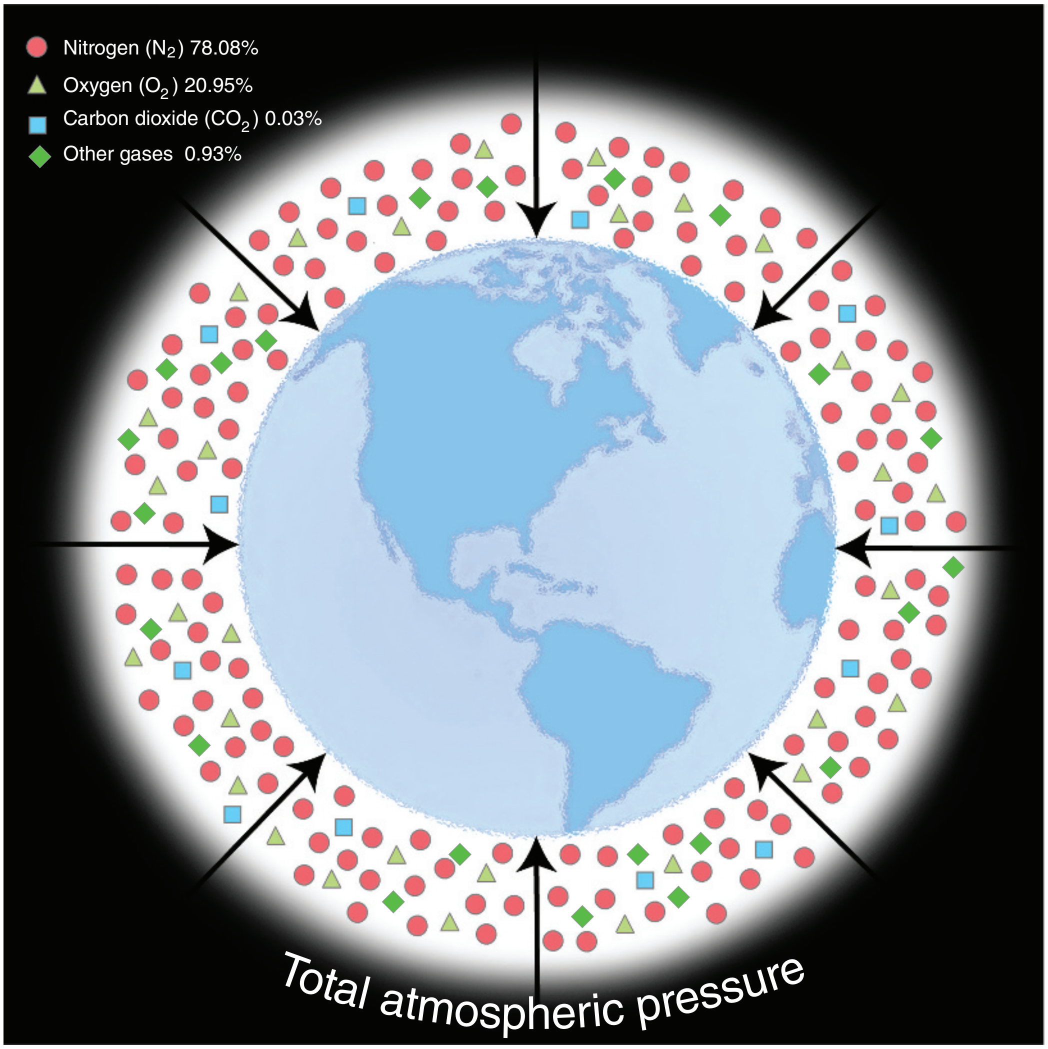
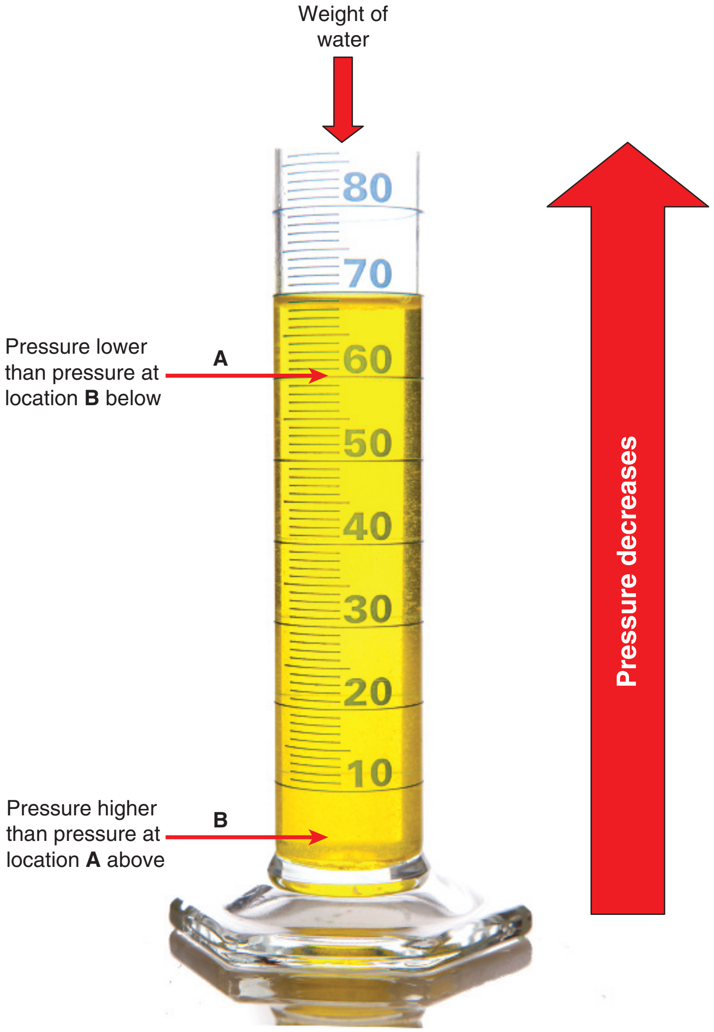

● Nitrogen (N_2) 78.08%
▲ Oxygen (O_2) 20.95%
■ Carbon dioxide (CO_2) 0.03%
◆ Other gases 0.93%
Total atmospheric pressure

FIGURE 2-3 Pressures exerted at different locations by the weight of a column of water. The pressure at point A is 10 cm H_2O—based on the height of water in centimeters above point A. The pressure at point B is 70 cm H_2O—based on the height of water in centimeters above point B.


Weight of water
80
70
60
50
40
30
20
10
Pressure lower than pressure at location **B** below
A
Pressure higher than pressure at location **A** above
B
Pressure decreases

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the bottom to the top of the water column. Simply stated: the pressure at any point in a water column is determined by the height of water above it.

Similar to the pressure generated by the weight of water, Figure 2–4 illustrates how the weight of gas molecules—which determines the P_B or force—in a column of atmospheric air progressively decreases with increasing altitude. Like the water column, the P_B at any given point is determined by the weight of the air molecules above it. Take a moment and compare the parallel concepts presented in both Figure 2–3 and Figure 2–4. In addition, note that the air molecules (shown in Figure 2–4) are close to each other (i.e., denser) near sea level. This is because the collective gas molecular weights—of all five atmospheric layers—are pushing down and compressing gas molecules near sea level.

In contrast, at higher elevations there is less air pushing down from above—thus, allowing the air molecules to move further away from each other—commonly referred to as "thinner air." This is why one often feels an increased pressure in one's ears when flying in a plane or skiing high in the mountains. In these examples, the atmospheric pressure is less than the pressure inside the body. It is also interesting to note that the boiling point of water decreases at higher elevations—since the P_B above the surface of the water is less at higher elevations than at sea level (Figure 2–5).

FIGURE 2-4 The weight of gas molecules—that is, the P_B—in a column of atmospheric air progressively decreases with increasing altitude.

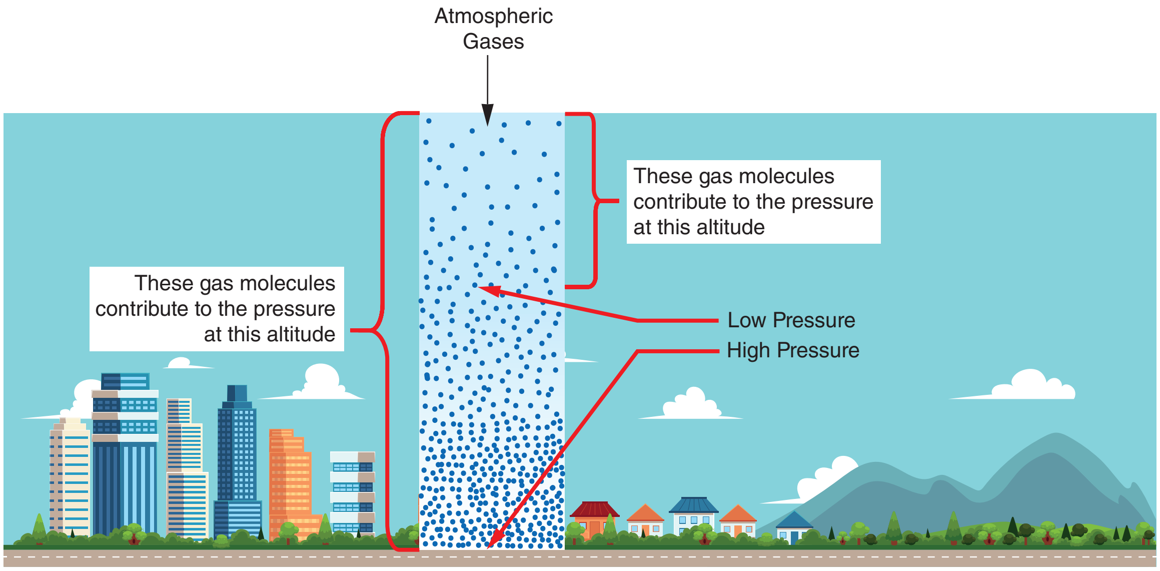
Atmospheric Gases
These gas molecules contribute to the pressure at this altitude
These gas molecules contribute to the pressure at this altitude
Low Pressure
High Pressure

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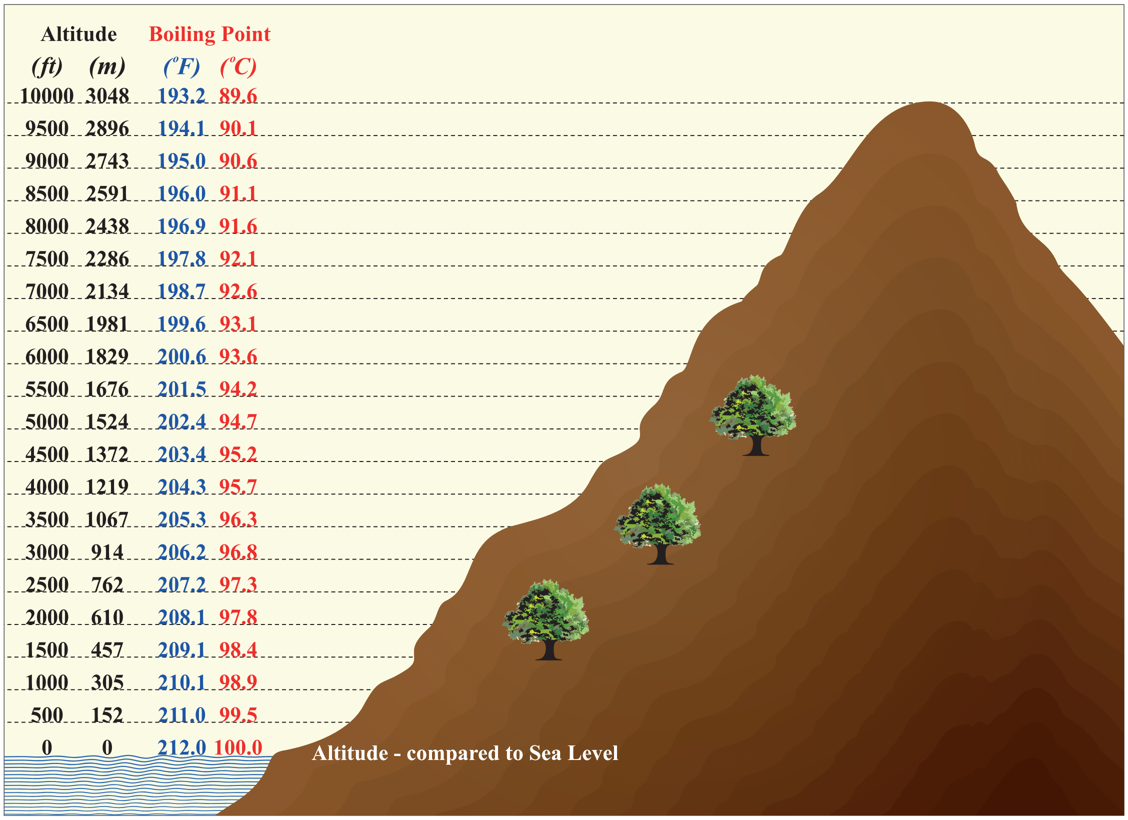
FIGURE 2-5 Boiling point of water at different altitudes. Note that the boiling point progressively decreases at higher elevations.



Altitude (ft)	Altitude (m)	Boiling Point (°F)	Boiling Point (°C)
10000	3048	193.2	89.6
9500	2896	194.1	90.1
9000	2743	195.0	90.6
8500	2591	196.0	91.1
8000	2438	196.9	91.6
7500	2286	197.8	92.1
7000	2134	198.7	92.6
6500	1981	199.6	93.1
6000	1829	200.6	93.6
5500	1676	201.5	94.2
5000	1524	202.4	94.7
4500	1372	203.4	95.2
4000	1219	204.3	95.7
3500	1067	205.3	96.3
3000	914	206.2	96.8
2500	762	207.2	97.3
2000	610	208.1	97.8
1500	457	209.1	98.4
1000	305	210.1	98.9
500	152	211.0	99.5
0	0	212.0	100.0

Altitude - compared to Sea Level

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Finally, it is important to stress that the percentage of each atmospheric gas—that is, nitrogen at 78.08 percent, oxygen at 20.95 percent, and carbon dioxide at 0.03 percent—does not change at higher elevations. The percentage of all the atmospheric gases remains the same throughout each atmospheric layer. Only the P_B falls at higher elevations. Figure 2–6 provides an overview summary of the P_B at different altitudes.

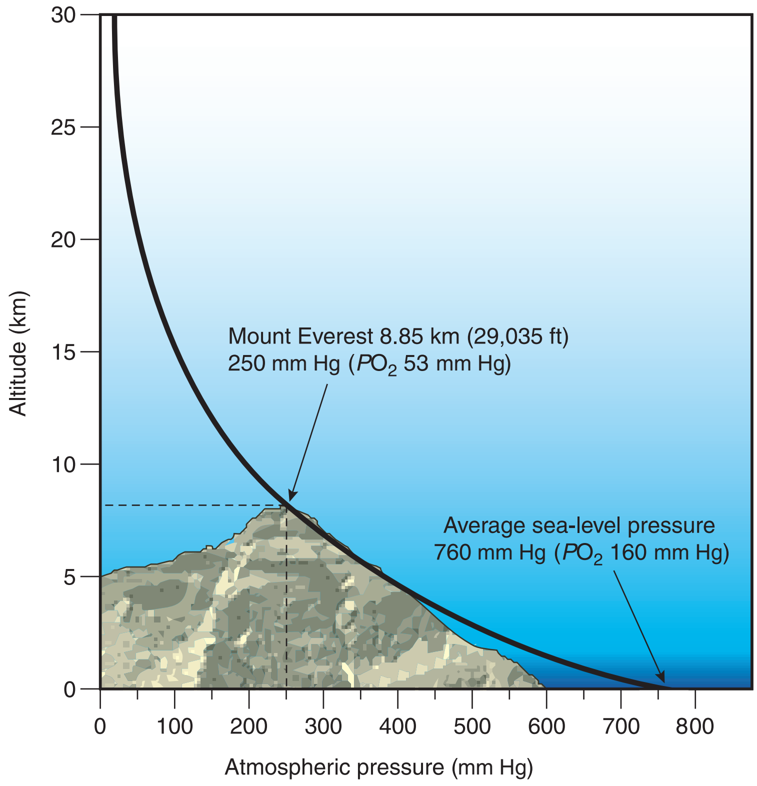
Measuring Units Used to Quantify the Atmospheric Pressure—and Their Application to the Pulmonary Ventilating Pressures

As explained in Figure 2–7, the P_B can be measured with a mercury barometer. At sea level under standard conditions, the P_B is 760 mm Hg.[1] Although there are a number of measuring units used to quantify the P_B, pulmonary ventilating pressures are most commonly expressed as either (1) **millimeters of mercury (mm Hg)**—also called torr, or (2) **centimeters of water (cm H_2O)**. The respiratory therapist must be familiar with both of these pressure units and, importantly, know how to covert from one pressure unit to another.

The conversion factors are as follows:

- mm Hg (torr) to cm H_2O: 1 mm Hg ÷ 0.7355 (factor) = 1.36 cm H_2O
- cm H_2O to mm Hg: 1 cm H_2O × 1.36 (factor) = 1.36 mm Hg

FIGURE 2-6 Overview summary of the progressively decreasing P_B from the ground upward.



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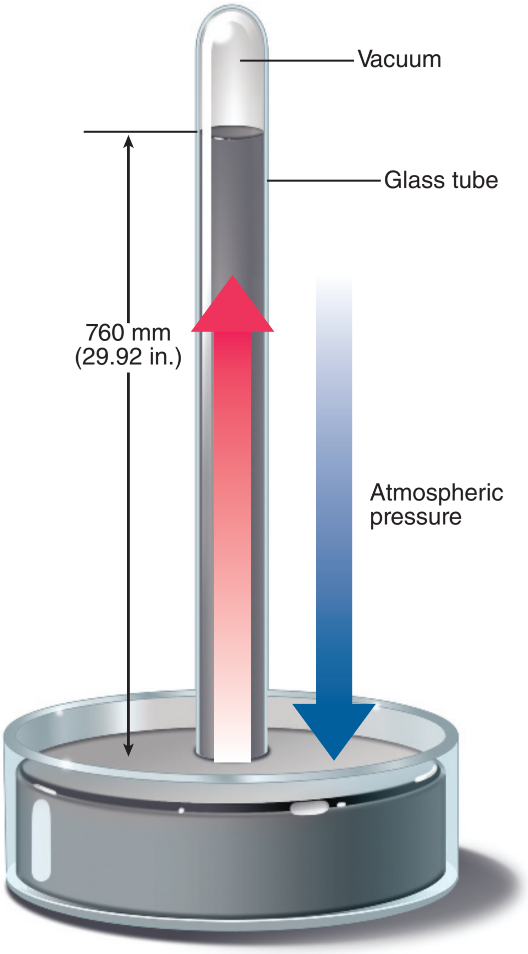
[1] Depending on the weather conditions, the atmospheric pressure (barometric pressure) can widely vary. The pressure of 760 mm Hg is an excellent reference point to discuss the mechanism of pulmonary ventilation. A PB of 760 mm Hg is equal to 1033 cm H_2O, 14.7 psi, 29.9 in Hg, 101.3 kPa, or 1013.25 millibars.

FIGURE 2-7 Mercury barometer. The standard mercury barometer is composed of a vacuum-filled glass tube of about 30 in. (76 cm) in height. The glass column is closed at one end and open at the other. The open end of the tube is placed in a mercury-filled base that interfaces with the atmospheric pressure. Relative to (1) the weight of the mercury in the column and (2) the atmospheric forces exerted on the mercury reservoir, the mercury moves up or down the column—similar to a liquid moving up a straw in a glass of water. In other words, the weight of the air pressing down on the surface of the mercury in the open dish pushes the mercury down into the dish and up the tube.

The greater the air pressure pushing down on the mercury surface, the higher up the tube the mercury will be forced. For example, during high barometric pressure periods, more force is exerted on the mercury reservoir—thus, forcing the mercury to climb higher up the glass column. On the other hand, during low-pressure periods, less force is exerted on the mercury reservoir—thus allowing the mercury to move down the glass column. Under standard conditions at sea level, the barometric pressure (P_B) causes the mercury to move up the glass column to a height of 760 mm (29.92 in.). This pressure can also be expressed in atmosphere units: atmospheric pressure = 760 mm Hg = 1 atm.

It should be noted that gas pressure values (e.g., P_{O_2}, P_{CO_2}, N_2) may be described as either mm Hg or torr. *Torr* was named after Evangelista Torricelli, an Italian physicist and mathematician, who discovered the principle of the mercury barometer in 1644. In honor of Torricelli, the torr was defined as a unit of pressure equal to 1 mm Hg—i.e., 1 torr = 1 mm Hg.

Blood pressure values and barometric pressure (i.e., atmospheric pressure) are always expressed in mm Hg.



Thus, a normal P_B at sea level can be expressed as either of 760 mm Hg or 1033 cm H_2O (760 ÷ 0.7355 = 1033.31 cm H_2O)—depending on which pressure unit measurement is used.[2]

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[2] Although the mm Hg and cm H_2O are the most common pressure units used for pulmonary pressure changes, they do not represent the SI standard (International System of Units). The SI unit for pressure is the kilopascal (kPa); 1 kPa = 7.5 mm Hg or 10.2 cm H_2O.

When the pulmonary pressures—mm Hg or cm H_2O—are used to describe ventilation pressures, they are always referenced to the atmospheric pressure and given a baseline value of zero. In other words, even though the atmospheric pressure at sea level is 760 mm Hg (or 1033 cm H_2O), it is designated as 0 mm Hg (or 0 cm H_2O). Thus, when the pulmonary pressure increases by $+10$ mm Hg (13.6 cm H_2O) during a positive-pressure breath, the pressure actually increases from 760 to 770 mm Hg (1033 to 1046.6 cm H_2O).

There are three more ways to further drive this important pressure relationship home:

- A pressure of -5 mm Hg in the trachea means the pressure in the trachea is lower than the atmospheric pressure by 5 mm Hg ($760 - 5 = 755$ mm Hg).
- A positive pressure of $+5$ mm Hg in the alveoli means the pressure in alveoli is higher than the atmospheric pressure by 5 mm Hg ($760 + 5 = 765$ mm Hg).
- A zero pressure in the trachea means the pressure in the trachea is equal to the atmospheric pressure ($760 - 760 = 0$ mm Hg).

With this fundamental understanding, the reader is prepared to examine the pressure relationships that normally exist throughout the thoracic cavity during a normal breathing cycle.

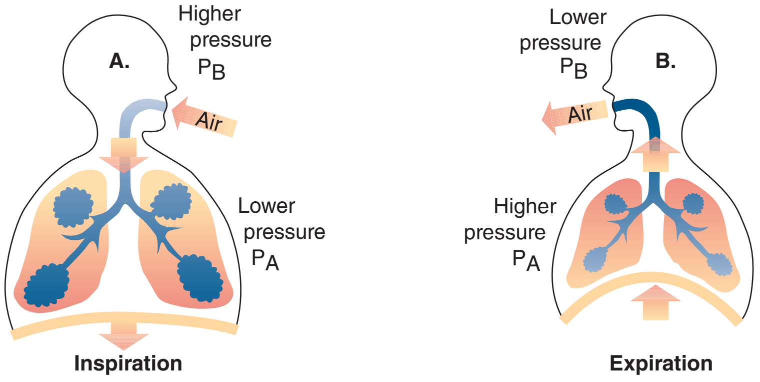
Pressure Gradients (Pressure Differences)

A gas or liquid always moves from an area of high pressure to an area of low pressure. In other words, for gas to flow from one point to another, there must be a "pressure difference" between the two points. In pulmonary physiology, a pressure difference is called a **pressure gradient**. Gas always moves "down" its pressure gradient—which means that gases always move from a high-pressure area to a low-pressure area. The mechanisms of pulmonary ventilation that create a pressure gradient are known as the **primary principles of ventilation**.

For example, when the atmospheric pressure is 760 mm Hg, the air pressure in the alveoli at **end-expiration**—and just before the beginning of another inspiration (pre-inspiration)—also exerts a pressure of 760 mm Hg. This explains why air is neither entering nor leaving the lungs at end-expiration and pre-inspiration. In other words, for pulmonary ventilation to occur, a mechanism must first be established that causes a pressure gradient between the atmosphere and the intra-alveoli.

As shown in Figure 2–8A, when the atmospheric pressure is higher than intra-alveoli pressure, air moves down the gas pressure gradient. In this case, gas moves from the atmosphere to the alveoli—and

FIGURE 2-8 The primary principle of ventilation: Gas always moves down a pressure gradient—that is, gas always moves from a high-pressure area to a lower-pressure area. **A.** During inspiration, the barometric pressure (P_B) is greater than the alveolar pressure (P_A). **B.** During expiration, the alveolar pressure is higher than the barometric pressure.



inspiration occurs. On the other hand, when the intra-alveolar pressure is greater than the atmospheric pressure, air again moves down a pressure gradient. In this case, air flows from the alveoli to the atmosphere—and expiration occurs.

The bottom line is this: for either inspiration or expiration to occur, the mechanisms of pulmonary ventilation must first establish a means to create (1) a pressure gradient for inspiration, in which the intra-alveolar pressure (P_{alv}) is lower than the atmospheric pressure (or barometric pressure, P_B), and (2) a pressure gradient for expiration, in which the intra-alveolar pressure is greater than the atmospheric pressure (Figure 2–8B).

Boyle's Law and Its Relationship to Pressure Gradients in Ventilation

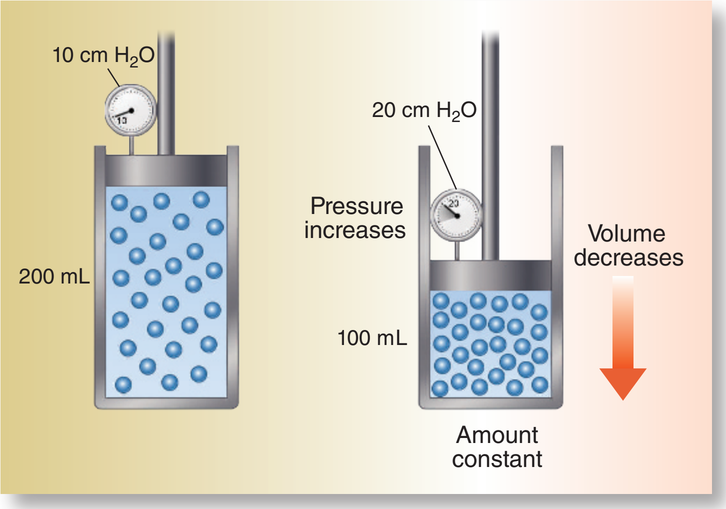
To fully comprehend how the pressure gradients for inspiration and expiration are produced, an understanding of how **Boyle's law** works to create pressure changes throughout the thoracic cavity during inspiration and expiration is absolutely essential.

Boyle's law ($P_1 \times V_1 = P_2 \times V_2$) states a volume of gas varies inversely proportional to its pressure at a constant temperature. For example, if an airtight container, which has a volume of 200 mL and a pressure of 10 cm H_2O, has its volume reduced 50 percent (100 mL), the new pressure in the container will double—that is, increase to 20 cm H_2O (Figure 2–9). This example can be computed as follows:

$$\begin{aligned} P_2 &= \frac{P_1 \times V_1}{V_2} \\ &= \frac{10 \text{ cm } H_2O \times 200 \text{ mL}}{100 \text{ mL}} \\ &= 20 \text{ cm } H_2O \end{aligned}$$

In applying Boyle's law to the mechanics of ventilation, it should be understood that when the thoracic cavity increases in size (increase in volume)—caused by the downward contraction of the diaphragm during inspiration—the pressure in the thoracic cavity decreases. This action causes air to move down the pressure

FIGURE 2-9 Boyle's law states a volume of gas varies inversely proportional to its pressure at a constant temperature. For example, as shown in this figure, if the pressure on a gas increased from 10 cm H_2O to 20 cm H_2O, the gas volume would decrease from 200 mL to 100 mL. In other words, doubling the pressure reduces the volume by half.



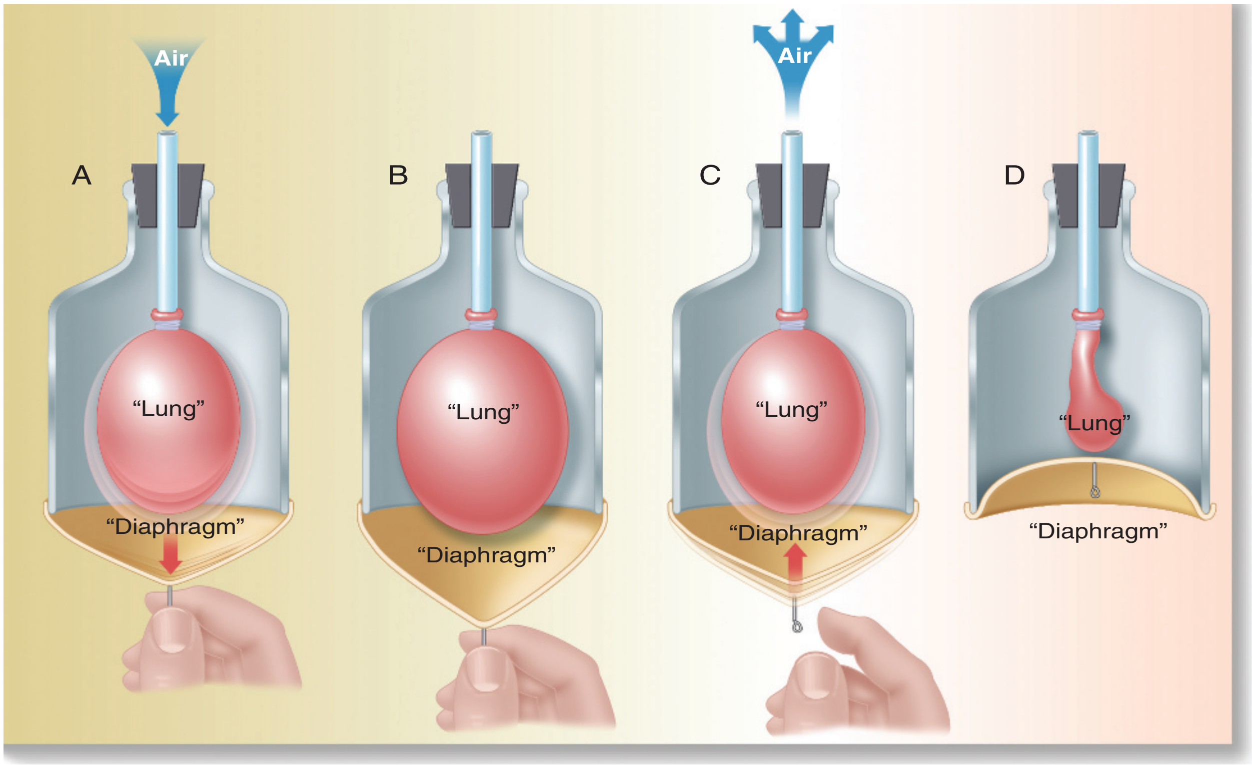
gradient from the atmosphere to the alveoli. On the other hand, when the thoracic cavity decreases in size (decrease in volume)—caused by the relaxation of the diaphragm during expiration—the pressure in the thoracic cavity increases. This action causes air to move down the pressure gradient from the alveoli to the atmosphere.

Balloon Model of Ventilation

The mechanisms of ventilation are often visually demonstrated by using a balloon in a bell-shaped jar (Figure 2–10). The bell-shaped jar represents the rib cage (thoracic cavity). The rubber sheet across the bottom of the jar represents the diaphragm. The balloon represents the lung. The space between the outside of the balloon and the inside of the jar represents the pleural space. The tube connected to the balloon and the cork at the top of the jar represents the trachea—which provides the only passageway between the inside of the balloon (lung) and the atmosphere.

To simulate **inspiration** the diaphragm is pulled downward, causing the size of the thoracic cavity to increase (increased volume)—which, in turn, causes the pleural pressure (P_{pl}) to decrease (remember, according to Boyle's law, as volume increases, pressure decreases). Because the balloon is composed of a thin stretchy, rubbery material (similar to the elastic tissue of the normal lung), the decrease in the P_{pl} is transmitted to the inside of the balloon. This mechanism causes a pressure gradient between the inside of the balloon and the atmosphere. Because the atmospheric pressure is higher than the pressure inside of the balloon—that is, a pressure gradient exists—gas from the atmosphere moves down the tube into the balloon (Figure 2–10A).

FIGURE 2-10 Balloon model of ventilation. **A.** Inspiration, caused by downward movement of the rubber sheet (diaphragm). **B.** End-inspiration (equilibrium point, no gas flow). **C.** Expiration, caused by the elastic recoil of the diaphragm upward movement. **D.** End-expiration (equilibrium point, no gas flow).



The gas flow continues until the pressure inside the balloon "equals" the pressure in the atmosphere—the **equilibrium point** (zero pressure point). Once the *equilibrium point* is reached, gas flow stops. This period of no gas flow represents **end-inspiration** (Figure 2–10B).

To simulate **expiration**, the elastic diaphragm is allowed to recoil upward, causing the size of the thoracic cavity to decrease (decreased volume)—which, in turn, causes the intrapleural pressure to increase (remember, according to Boyle's law, as volume decreases, pressure increases). Again, because the balloon is composed of a thin rubbery material, the increase in P_{pl} is transmitted to the inside of the balloon. This mechanism causes a pressure gradient between the inside of the balloon and the atmosphere. Because the pressure is now higher inside the balloon than the atmosphere—that is, a pressure gradient exists—gas from inside the balloon flows through the tube into the atmosphere (Figure 2–10C).

The gas flow will continue until the pressure inside the balloon equals the pressure in the atmosphere. Once the equilibrium point is reached, gas flow stops. This period of no gas flow represents **end-expiration** (Figure 2–10D).

The entire simulated breathing sequence—that is, inspiration, end-inspiration, expiration, and end-expiration—represents one **respiratory cycle**.

Primary Mechanisms of Ventilation Applied to the Human Airways

Figure 2–11 applies the same pressure gradient principle illustrated in the balloon model to the human thoracic cavity, lungs, diaphragm, and airways. During **inspiration**, the diaphragm contracts downward, causing the size of the thoracic cavity to increase (increased volume). This action causes the pleural pressure (P_{pl}) to decrease. Because the lung is composed of a thin elastic tissue, the decrease in the P_{pl} is transmitted to the inside of the alveoli—which, in turn, causes the intra-alveolar pressure to decrease. This mechanism causes a pressure gradient to develop between the intra-alveoli pressure and the atmospheric pressure. Because the atmospheric pressure is higher than the intra-alveolar pressure—that is, a pressure gradient exists—gas from the atmosphere moves through the tracheobronchial tree to the alveoli (Figure 2–11A).

The gas flow will continue until the intra-alveolar pressure and the atmospheric pressure are in equilibrium. Once the equilibrium point is reached, gas flow stops. This period of no gas flow is the **end-inspiration** (or pre-expiration) phase of the respiratory cycle (Figure 2–11B).

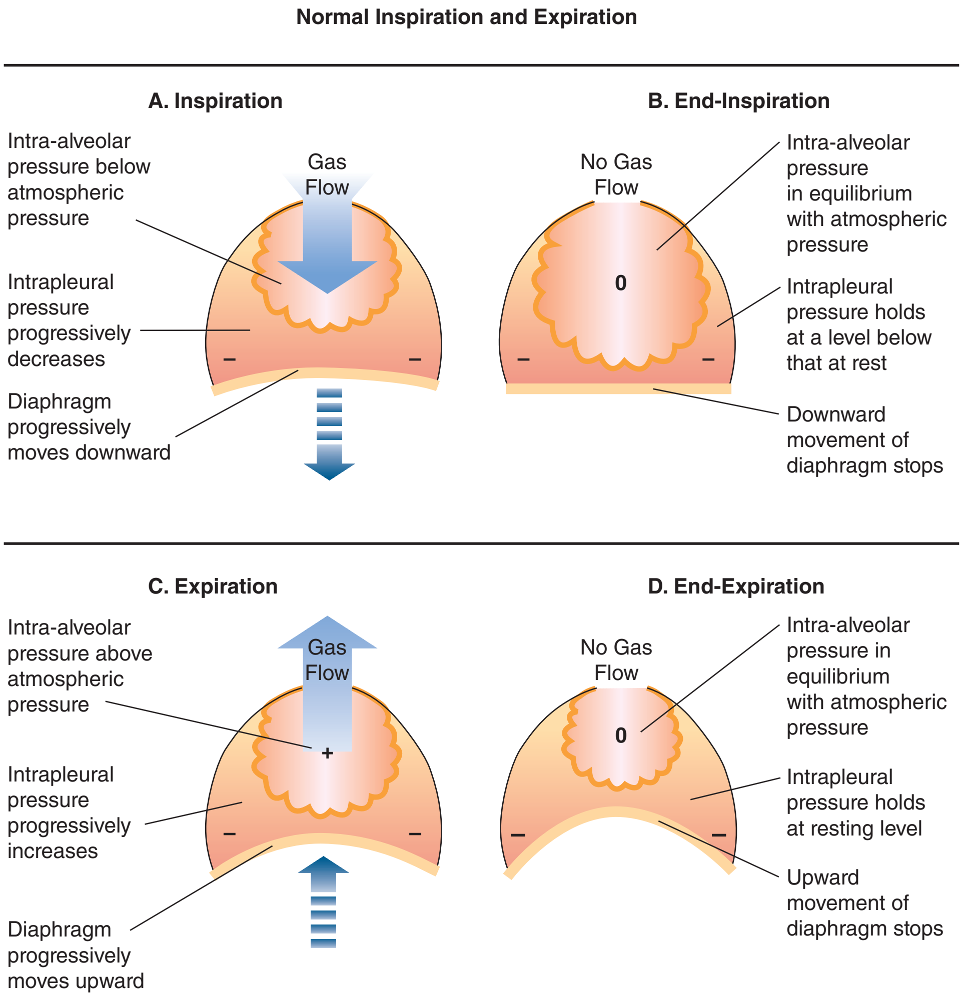
During **expiration**, the diaphragm relaxes and moves upward, causing the size of the thoracic cavity to decrease (decreased volume). This action causes the pleural pressure (P_{pl}) to increase. Again, because the lung is composed of a thin elastic tissue, the increase in the P_{pl} is transmitted to the inside of the alveoli—which, in turn, causes the intra-alveolar pressure to increase. This mechanism causes a pressure gradient between the intra-alveoli pressure and the atmospheric pressure. Because the intra-alveolar pressure is higher than the atmospheric pressure—that is, a pressure gradient exists—gas from the alveoli moves through the tracheobronchial tree to the atmosphere (Figure 2–11C).

The gas flow will continue until the intra-alveolar pressure and the atmospheric pressure are in equilibrium. Once equilibrium point is reached, gas flow stops. This period of no gas flow is the **end-expiration** (or pre-inspiration) phase of the respiratory cycle (Figure 2–11D).

Under normal conditions, the intrapleural pressure—during both inspiration and expiration—is always below the barometric pressure. This is because the lungs have a natural tendency to recoil inward, and the chest wall has a natural tendency to expand outward. These two opposing forces generate a subatmospheric pressure—that is, negative pleural pressure—between the parietal and visceral pleurae. With normal breathing at rest, the excursion of the diaphragm is about 1.5 cm, and the normal pleural pressure change is about 3 to 6 cm H_2O pressure (2 to 4 mm Hg). During a deep inspiration, however, the diaphragm may move as much as 6 to 10 cm—which can cause the pleural pressure to drop to as low as -50 cm H_2O subatmospheric pressure. During a forced expiration, the pleural pressure may climb to between $+70$ and 100 cm H_2O above atmospheric pressure.

To summarize, it should be clear that a complete understanding of Boyle's law and its relationship to pressure gradients during the respiratory cycle is essential to understanding the mechanisms of

FIGURE 2-11 How the excursion of the diaphragm affects the intrapleural pressure, intra-alveolar pressure, and bronchial gas flow during inspiration and expiration.


Normal Inspiration and Expiration
A. Inspiration
Intra-alveolar pressure below atmospheric pressure
Gas Flow
Intrapleural pressure progressively decreases
–
–
Diaphragm progressively moves downward
B. End-Inspiration
No Gas Flow
0
Intra-alveolar pressure in equilibrium with atmospheric pressure
Intrapleural pressure holds at a level below that at rest
–
–
Downward movement of diaphragm stops
C. Expiration
Intra-alveolar pressure above atmospheric pressure
Gas Flow
+
Intrapleural pressure progressively increases
–
–
Diaphragm progressively moves upward
D. End-Expiration
No Gas Flow
0
Intra-alveolar pressure in equilibrium with atmospheric pressure
Intrapleural pressure holds at resting level
–
–
Upward movement of diaphragm stops

ventilation. In other words, the fundamental principle of ventilation is based on these two pressure gradient facts: (1) gas always flows from an area of high pressure to an area of low pressure—that is, a pressure gradient must exist (e.g., inspiration and expiration), and (2) there is no gas movement when the pressure gradient is zero—that is, there is no gas flow when the pressure between two points is equal (e.g., end-inspiration and end-expiration).

Clinical Connection 2-1

Inspiratory Intercostal Retractions

At the bedside, the respiratory therapist (RT) will see **inspiratory intercostal retractions** as inward movements of the tissue between the ribs, above the clavicle, or below the rib cage. This is a key indicator of severe respiratory distress—especially in infants (Figure 2–12). These are commonly referred to as intercostal retractions, supraclavicular retractions, or subcostal retractions, respectively. Additionally,

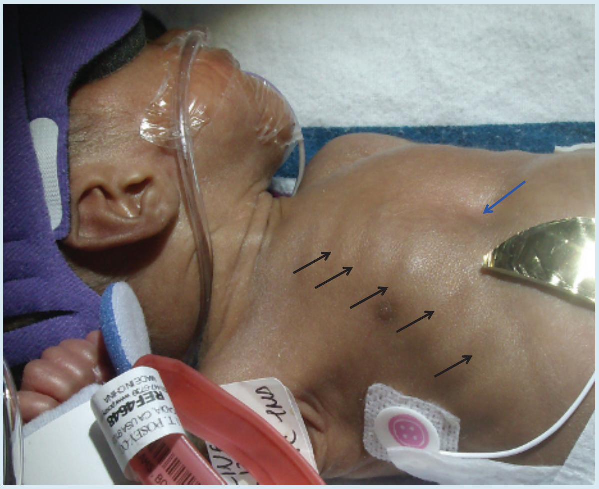
Clinical Connection 2-1, Continued

the chest of the newborn is composed of a large amount of cartilage and is very flexible. The RT can actually observe these flexible ribs move inward on inspiration. When this happens, the infant's inspiratory volume will be diminished.

The RT must be aware of any respiratory disorder that increases the work of breathing—for example, narrowing of the airway such as asthma or a stiff lung such as pneumonia—that can activate the muscles of inspiration to contract forcefully in an effort to generate a greater negative intrapleural and intra-alveolar pressure to draw in more air. The inspiratory retractions overlying the chest wall are a direct result of the increased negative intrapleural pressure.

Clinically, intercostal retractions are an excellent warning sign that the patient is experiencing severe respiratory distress. Although intercostal retractions can be seen in most patients with respiratory distress, they are common in the newborn infant with stiff lung—for example, **respiratory distress syndrome**. This is because the chest of the newborn is composed of a large amount of cartilage and is flexible. Retractions are often hard to see in the obese patient because of the extra tissue covering the chest.

FIGURE 2-12 Newborn infant showing intercostal retractions (black arrows) and substernal retractions (blue arrow).



Courtesy T. Des Jardins, WindMist LLC

Finally, the respiratory therapist must also know and understand the following five different types of pressure measurements commonly used in pulmonary physiology: **driving pressure**, **transrespiratory pressure**, **transmural pressure**, **transpulmonary pressure**, and **transthoracic pressure**. Once these measurements are understood, and the idea of pressure gradients are mastered, the differences between **normal spontaneous ventilation**, **positive-pressure ventilation**, and **negative-pressure ventilation** become crystal clear.

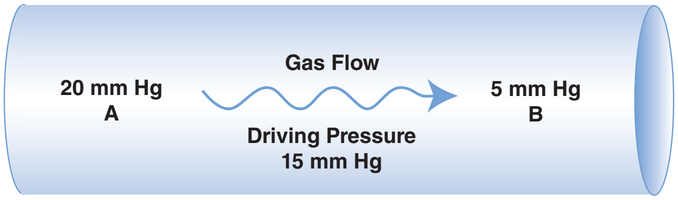
Driving pressure is the pressure difference between two points in a tube or vessel; it is the force moving gas or fluid through the tube or vessel. For example, if the gas pressure at the beginning of a tube is 20 mm Hg and the pressure at the end of the same tube is 5 mm Hg, then the driving pressure is 15 mm Hg. In other words, the force required to move the gas through the tube is 15 mm Hg (Figure 2–13).

Transrespiratory pressure (P_{rs}) (also called transairway pressure) is the difference between the barometric (atmospheric) pressure (P_B) and the alveolar pressure (P_{alv}). In other words, the P_{rs} is the pressure gradient difference between the mouth pressure (atmospheric pressure) and the alveolar pressure (P_{alv}).

$$P_{rs} = P_B - P_{alv}$$

For example, if the P_{alv} is 757 mm Hg and the P_B is 760 mm Hg during inspiration, then the P_{rs} is 3 mm Hg (Figure 2–14A).

FIGURE 2-13 Driving pressure. At point A, gas pressure is 20 mm Hg. At point B, gas pressure is 5 mm Hg. Thus, the driving pressure between point A and point B is 15 mm Hg.


Gas Flow
20 mm Hg
A
5 mm Hg
B
Driving Pressure
15 mm Hg

$$P_{rs} = P_B - P_{alv}$$
$$= 760 \text{ mm Hg} - 757 \text{ mm Hg}$$
$$= 3 \text{ mm Hg}$$

Or, if the P_{alv} is 763 mm Hg and the P_B is 760 mm Hg during expiration, then the P_{rs} is −3 mm Hg. Gas in this example, however, is moving in the opposite direction (Figure 2–14B). The P_{rs} causes airflow in and out of the conducting airways. In essence, the P_{rs} represents the driving pressure (the pressure difference between the mouth and the alveolus) that forces gas in or out of the lungs.

Transmural pressure (P_{tm}) is the pressure difference that occurs across the airway wall. The transmural pressure is calculated by subtracting the intra-airway pressure (P_{iaw}) from the pressure on the outside of the airway (P_{oaw}).

$$P_{tm} = P_{oaw} - P_{iaw}$$

Positive transmural pressure is said to exist when the pressure is greater within the airway than the pressure outside the airway. For example, if the P_{iaw} pressure is 765 mm Hg and the P_{oaw} is 760 mm Hg, there is a positive transmural pressure of 5 mm Hg (Figure 2–15A).

$$P_{tm} = P_{oaw} - P_{iaw}$$
$$= 765 \text{ mm Hg} - 760 \text{ mm Hg}$$
$$= 5 \text{ mm Hg (positive transmural pressure)}$$

FIGURE 2-14 Transrespiratory pressure (P_{rs}): the difference between the body surface pressure (P_{bs})* and the alveolar pressure (P_{alv}). Even though gas is moving in opposite directions in A and B, the transrespiratory pressure is 3 mm Hg in both examples.
*Note: In this illustration, the body surface pressure (P_{bs}) is equal to the barometric pressure (P_B).

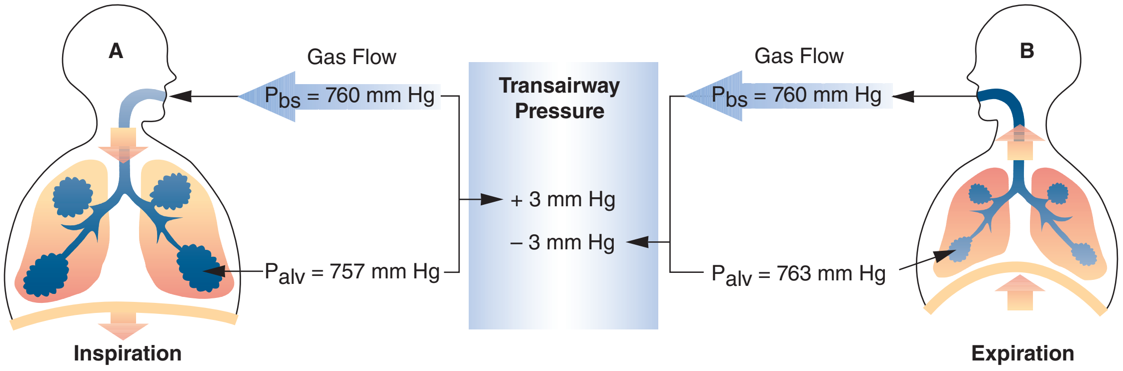
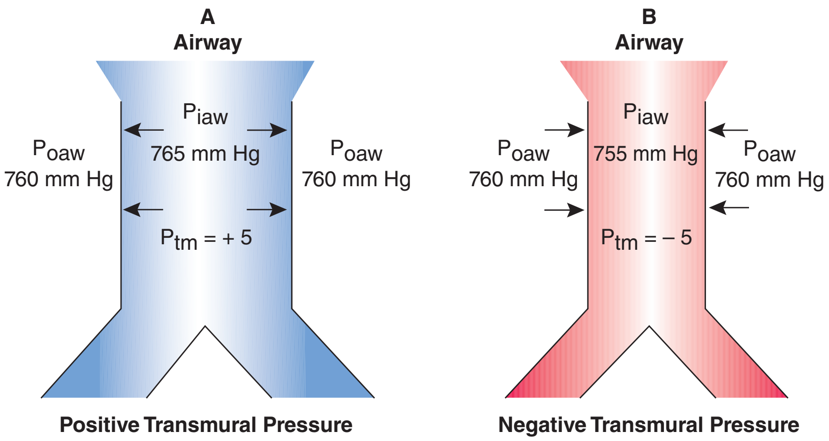

A
Gas Flow
Pbs = 760 mm Hg
Palv = 757 mm Hg
Inspiration
Transairway Pressure
+ 3 mm Hg
– 3 mm Hg
B
Gas Flow
Pbs = 760 mm Hg
Palv = 763 mm Hg
Expiration

FIGURE 2-15 Transmural pressure: the pressure difference that occurs across the wall of the airway. **A.** Airway with a positive transmural pressure. **B.** Airway with a negative transmural pressure.


A
Airway
P_{iaw}
765 mm Hg
P_{oaw}
760 mm Hg
P_{oaw}
760 mm Hg
P_{tm} = + 5
B
Airway
P_{iaw}
755 mm Hg
P_{oaw}
760 mm Hg
P_{oaw}
760 mm Hg
P_{tm} = – 5

Positive Transmural Pressure
+5 torr

Negative Transmural Pressure
–5 torr

Negative transmural pressure is said to exist when the pressure is greater outside the airway than the pressure inside the airway. For example, if the P_{iaw} pressure is 755 mm Hg and the P_{oaw} is 760 mm Hg, there is a negative transmural pressure of 5 mm Hg (Figure 2–15B).

Transpulmonary pressure (P_{tp}) is the difference between the alveolar pressure (P_{alv}) and the pleural pressure (P_{pl}).

$$P_{tp} = P_{alv} - P_{pl}$$

For example, if the P_{pl} is 755 mm Hg and the P_{alv} is 760 mm Hg (e.g., inspiration), then the P is 5 mm Hg (Figure 2–16A).

$$\begin{aligned} P_{tp} &= P_{alv} - P_{pl} \\ &= 760 \text{ mm Hg} - 755 \text{ mm Hg} \\ &= 5 \text{ mm Hg} \end{aligned}$$

Or, if the P_{alv} is 763 mm Hg and the P_{pl} is 758 mm Hg (e.g., expiration), then the P_{tp} is 5 mm Hg (Figure 2–16B). In the normal lung, the P_{alv} is always greater than the P_{pl}, which, in turn, maintains the lungs in an inflated state.

FIGURE 2-16 Transpulmonary pressure: the difference between the alveolar pressure (P_{alv}) and the pleural pressure (P_{pl}). This illustration assumes a barometric pressure (P_B) of 761 mm Hg.

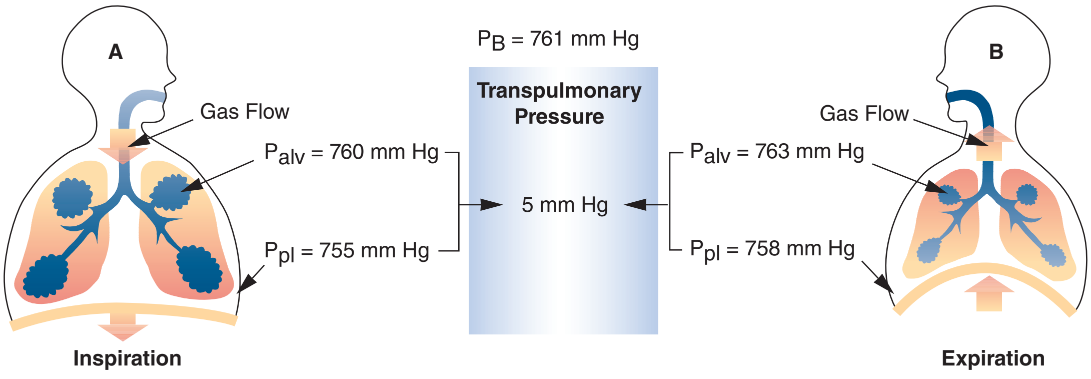
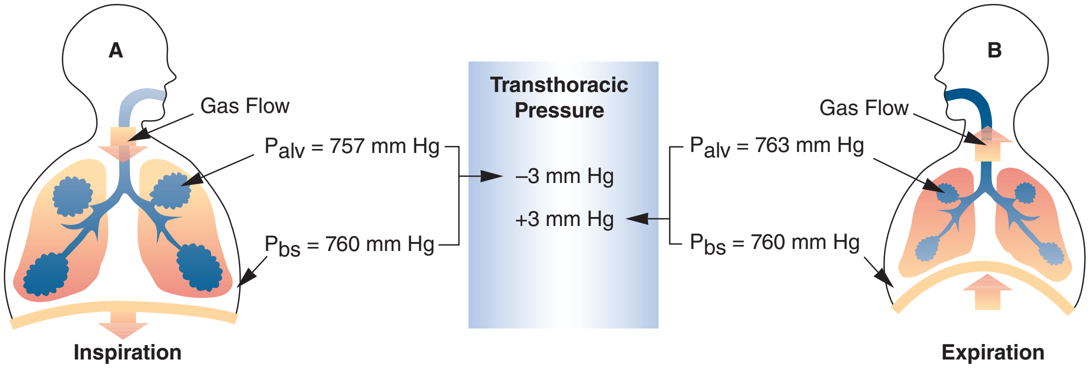

A
Gas Flow
P_{alv} = 760 mm Hg
P_{pl} = 755 mm Hg
P_B = 761 mm Hg
Transpulmonary Pressure
5 mm Hg
B
Gas Flow
P_{alv} = 763 mm Hg
P_{pl} = 758 mm Hg
Inspiration
Expiration

FIGURE 2-17 Transthoracic pressure: the difference between the alveolar pressure (P_{alv}) and the body surface pressure (P_{bs}). Note: In this illustration, the body surface pressure (P_{bs}) is equal to the barometric pressure (P_B).



Transthoracic pressure (P_{tt}) is the difference between the alveolar pressure (P_{alv}) and the body surface pressure (P_{bs}).

$$P_{tt} = P_{alv} - P_{bs}$$

For example, if the P_{alv} is 757 mm Hg and the P_{bs} is 760 mm Hg (e.g., inspiration), then the P_{tt} is −3 mm Hg (Figure 2–17A).

$$\begin{aligned} P_{tt} &= P_{alv} - P_{bs} \\ &= 757 \text{ mm Hg} - 760 \text{ mm Hg} \\ &= -3 \text{ mm Hg} \end{aligned}$$

Or, if the P_{alv} is 763 mm Hg and the P_{bs} is 760 mm Hg (e.g., expiration), then the P_{tt} is 3 mm Hg (Figure 2–17B). The P_{tt} is the pressure responsible for expanding the lungs and chest wall in tandem.

Technically, there is no real difference between the transrespiratory pressure (P_{rs}) and the transthoracic pressure (P_{tt}). The P_{tt} is merely another way to view the pressure differences across the lungs.

Clinical Connection 2-2

Abdominal Paradox (diaphragm fatigue)

During normal resting inspiration, the diaphragm descends, and the external intercostal muscles lift the ribs up and outward to increase thoracic volume. Per Boyle's law (see Figure 2–9), the increase in volume results in a decrease in intrathoracic pressure and a resultant inflow of gas for inspiration allowing air to passively move down the tracheobronchial tree from a high atmospheric pressure to a low alveolar pressure until equilibrium occurs. During passive exhalation, the diaphragm moves back to its upward resting position and the abdomen moves inward to fill the void as the diaphragm and lungs move upward. This action decreases the thoracic volume, which, in turn, increases the alveolar pressure and causes gas to move out of the lungs.

However, in cases of diaphragmatic paralysis (e.g., caused by phrenic nerve damage) or diaphragmatic fatigue—which is common with many types of pulmonary disorders where the inspiratory work of breathing may be excessively increased—an

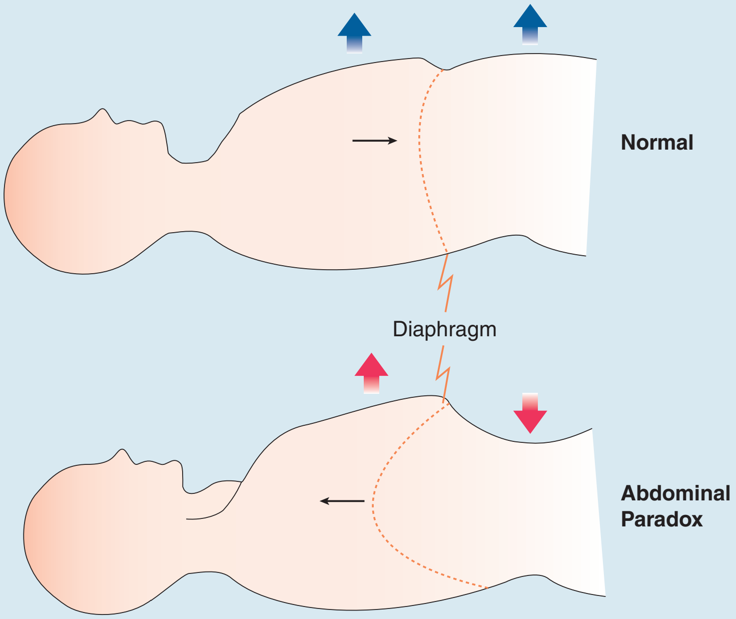
Clinical Connection 2-2, Continued

important abnormal breathing pattern is commonly seen. For example, during periods of increased work of breathing (WOB) in the patient with severe COPD, the diaphragm often becomes overly fatigued. As the diaphragm becomes ineffective, the accessory muscles of inspiration—that is, the external intercostal, scalene, sternocleidomastoid, pectorals major, and trapezius muscles—attempt to maintain ventilation by becoming more active. Unfortunately, this condition can alter the normal mechanics of breathing as follows:

As the accessory muscles of inspiration work to lift the ribs up and outward, the increase in thoracic volume will cause a resultant decrease in intrathoracic pressure. When the diaphragm is fatigued or paralyzed, it will be sucked upward by the negative intrathoracic pressure. During expiration, as the chest wall returns to its resting position, the thoracic volume decreases, and the intrathoracic pressure rises. The increased intrathoracic pressure, in turn, pushes the passive diaphragm downward and causes the abdomen to move outward. Thus, on observation, the chest wall expands with inspiration (which is normal), while the abdomen moves inwards (which is not normal). During exhalation, the chest wall decreases (which is normal), while the abdomen moves outward (which is not normal). This abnormal breathing pattern is known as **abdominal paradox** and is an important clinical observation in patients with paralysis or fatigue of the diaphragm (Figure 2–18).

A similar abnormal breathing pattern is commonly observed in the newborn infant with stiff lungs—caused, for example, by respiratory distress syndrome (RDS). In response to the low lung compliance, the infant—via their diaphragm—must generate a greater than normal negative pressure during inspiration. This action, in turn, causes their abdominal area to protrude outward (which is normal), and the substernal area and soft tissue between their ribs to move inward (which is not normal). During exhalation, the abdominal area moves inward and the substernal area and soft tissue between the ribs move back to their resting positions. This abnormal breathing pattern is known as the "**seesaw effect**" and is an important clinical observation in the newborn infant with low lung compliance (see Figure 2–12).

FIGURE 2-18 Abdominal paradox. When the diaphragm is fatigued or paralyzed, the chest wall expands with inspiration (which is normal), while the abdomen moves inwards (which is not normal). During exhalation, the chest wall decreases (which is normal), while the abdomen moves outward (which is not normal).



Clinical Connection 2-3

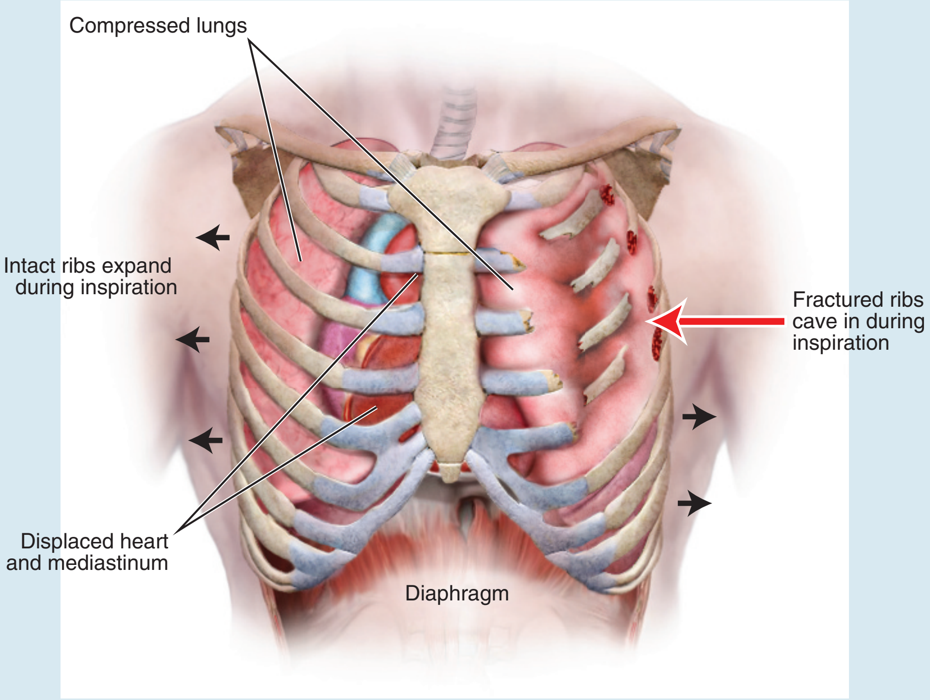
The Harmful Effects of Pressure Gradients When the Thorax Is Unstable

In the Clinical Application Case 1 (page 144), the respiratory therapist is called to assist in the care of a 22-year-old male motorcycle crash victim who presents in the emergency room with numerous abrasions, lacerations, and a very serious chest injury—multiple broken ribs over the right anterior chest. In this case, the RT must be aware of how (1) the **negative intrapleural pressure**, (2) the **transpulmonary pressure**, and (3) the **transthoracic pressure** all profoundly affect the patient's ability to breathe when the chest wall is unstable.

For example, each time the patient inhales, the transpulmonary and transthoracic pressure gradients cause his broken ribs to sink inward. This condition is called a **flail chest** (Figure 2–19). Figure 2–20 shows a chest X-ray of a right-sided flail chest. This movement causes the patient's inspiratory volume to decrease. During each exhalation, the pressure gradients cause the patient's broken ribs to bulge outward. This action causes some of the exhaled air from the unaffected lung to move into the affected lung—the lung directly under the broken ribs—rather than being exhaled out. The movement of air from one lung to another is known as a **pendelluft**.

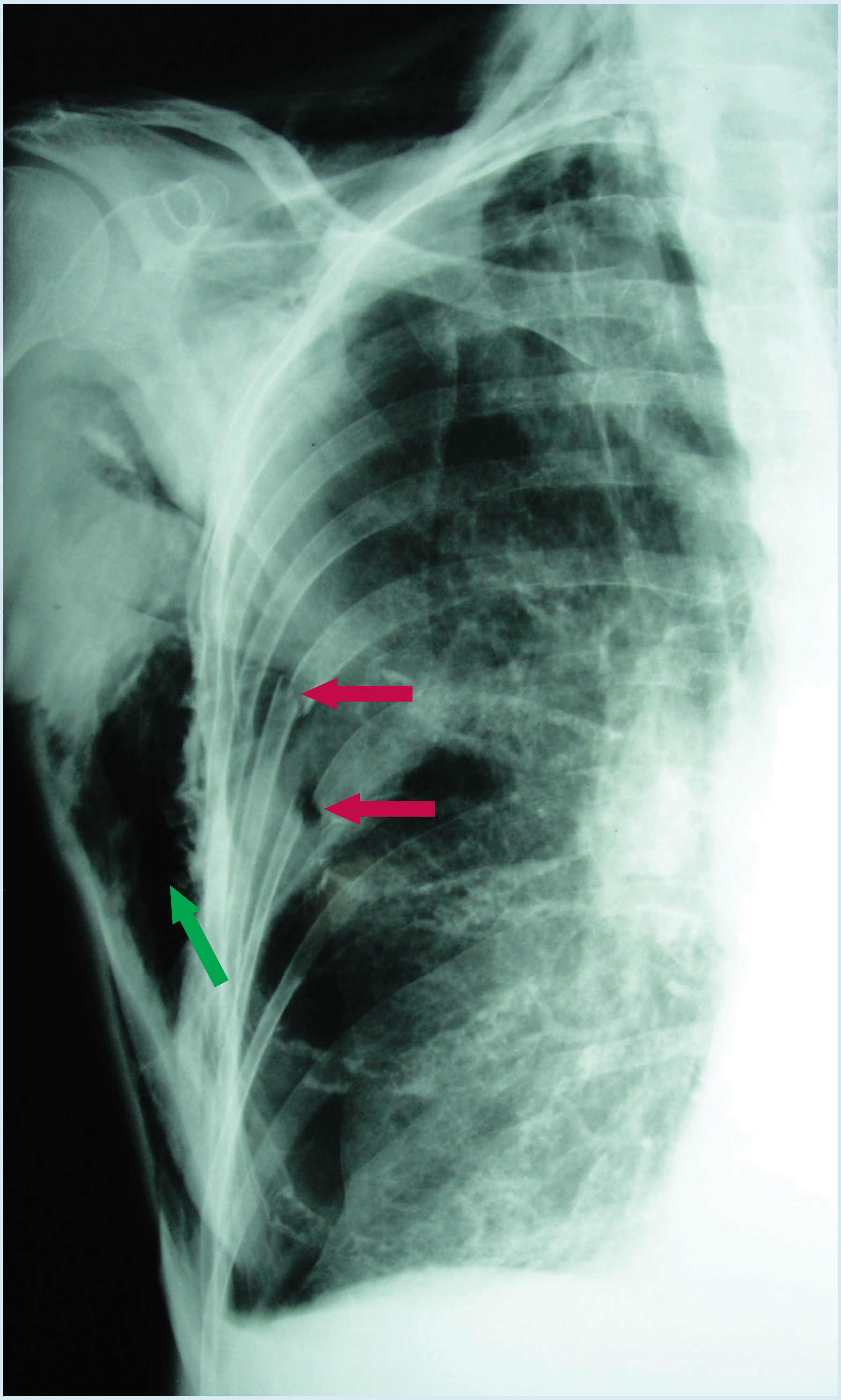
Case 1 also shows how the respiratory therapist must be aware of this inward movement of the chest—during each inspiration—and how it will work against the patient's ability to breathe. To correct this problem, the therapist must place the patient on a positive-pressure ventilator. The positive-pressure ventilator eliminates the negative intrapleural pressure changes during each inspiration—which, in turn, stops the adverse effects of the transpulmonary and transthoracic pressure gradients during inspiration. The respiratory therapist uses positive-pressure ventilation to prevent the flailed portion of the chest from affecting breathing and to provide time for the broken ribs to heal.

FIGURE 2-19 Flail chest. Pathology includes (1) double fracture of at least three or more adjacent ribs, (2) affected ribs cave in (flail) during inspiration, (3) atelectasis and lung collapse, (4) lung contusion or trauma, and (5) secondary pneumonia (e.g., from weak cough due to pain).


Compressed lungs
Intact ribs expand during inspiration
Fractured ribs cave in during inspiration
Displaced heart and mediastinum
Diaphragm

Clinical Connection 2-3, Continued

FIGURE 2-20 Right-sided flail chest. See red arrows for broken ribs. Note the **subcutaneous emphysema**—which is the presence of air in the subcutaneous tissues (green arrow). Subcutaneous emphysema is a common complication associated with chest trauma.



Courtesy T. Des Jardins, WindMist LLC

Elastic Properties of the Lung and Chest Wall

Both the lungs and the chest wall each have their own elastic properties—and, under normal conditions, each elastic system works against the other. That is, the chest wall has a natural tendency to move outward or to expand as a result of the bones of the thorax and surrounding muscles. The lungs have a natural tendency to move inward or collapse because of the natural elastic properties of the lung tissue. This lung–chest wall relationship is often compared to that of two springs working against each other—that is, the chest wall works to spring outward; the lungs work to recoil inward. Clinically, the elastic forces of the lungs are routinely evaluated by measuring the lung compliance.

Lung Compliance

As illustrated by the pressure-volume (P-V) curve in Figure 2–21, how readily the elastic force of the lungs accepts a volume of inspired air is known as **lung compliance** (C_L). C_L is defined as the *change in lung volume* (ΔV) per *unit pressure change* (ΔP). Mathematically, C_L is expressed in liters per centimeter of water pressure (L/cm H_2O). In other words, C_L determines how much air, in liters, the lungs will accommodate for each centimeter of water pressure change (e.g., each transpulmonary pressure change).

For example, if an individual generates a negative pleural pressure change of 5 cm H_2O during inspiration, and the lungs accept a new volume of 0.5 L (500 mL) of gas, the C_L of the lungs would be expressed as 0.1 L/cm H_2O (100 mL/cm H_2O):

$$
\begin{aligned}
C_L &= \frac{\Delta V\ (\text{L})}{\Delta P\ (\text{cm } H_2O)} \\
&= \frac{0.5 \text{ L of gas}}{5(\text{cm } H_2O)} \\
&= 0.1 \text{ L/cm } H_2O \text{ (or 100 mL/cm } H_2O)
\end{aligned}
$$

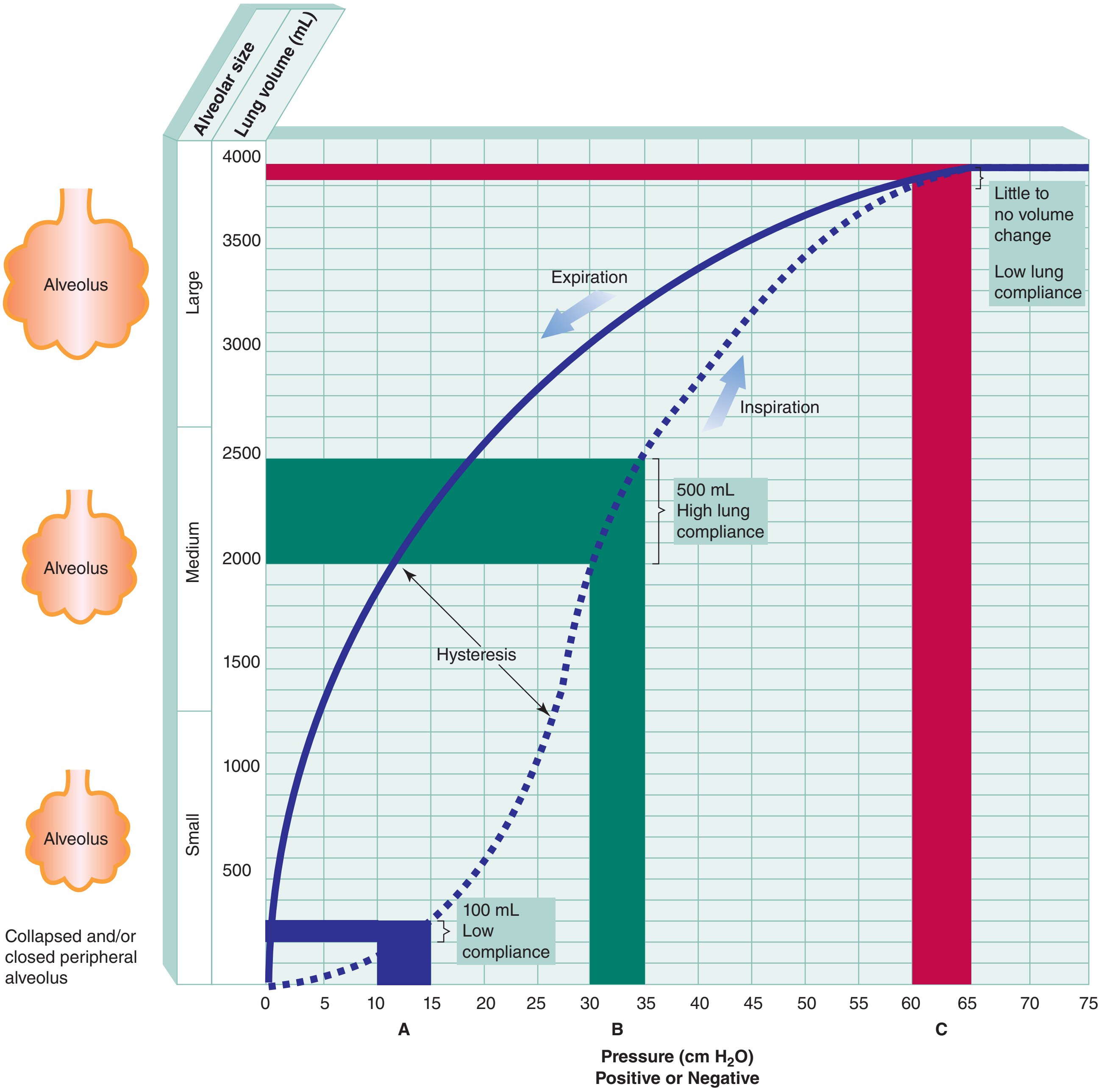
It is irrelevant whether the change in driving pressure is in the form of positive or negative pressure. In other words, a negative 5-cm H_2O pressure generated in the pleural space, around the lungs, will produce the same volume change as a positive 5-cm H_2O pressure delivered to the tracheobronchial tree (e.g., by means of a mechanical ventilator).

Also note in Figure 2–21 that the deflation portion of the P-V curve takes a different path back to the top of the FRC—illustrating that at the same distending pressure, the lung volume is greater during deflation than inflation. This phenomenon is called **hysteresis**. A hysteresis is seen in the P-V curve because more energy is required to inflate the lungs than to deflate them. This is because the primary mechanism of lung inflation and deflation involves the sequential opening (called recruitment) and closing (called de-recruitment) of peripheral alveoli. In other words, at the beginning of a normal inspiration, many peripheral alveoli are closed. As inspiration continues, some of the peripheral alveoli are forced open—that is, recruited—by the increased transpulmonary pressure. In fact, during normal inspirations, the lung volume actually increases—to a large extent—because of the newly recruited alveoli, not because previously open alveolar diameters increase.

In short, more energy is needed during inspiration for the recruitment process—mostly to overcome the molecular adhesive forces of surface tension. These molecular adhesive forces are essentially absent in alveoli that are already open during exhalation. Thus, more lung volume is present at any given transpulmonary pressure during exhalation than inspiration (see Figure 2–21).

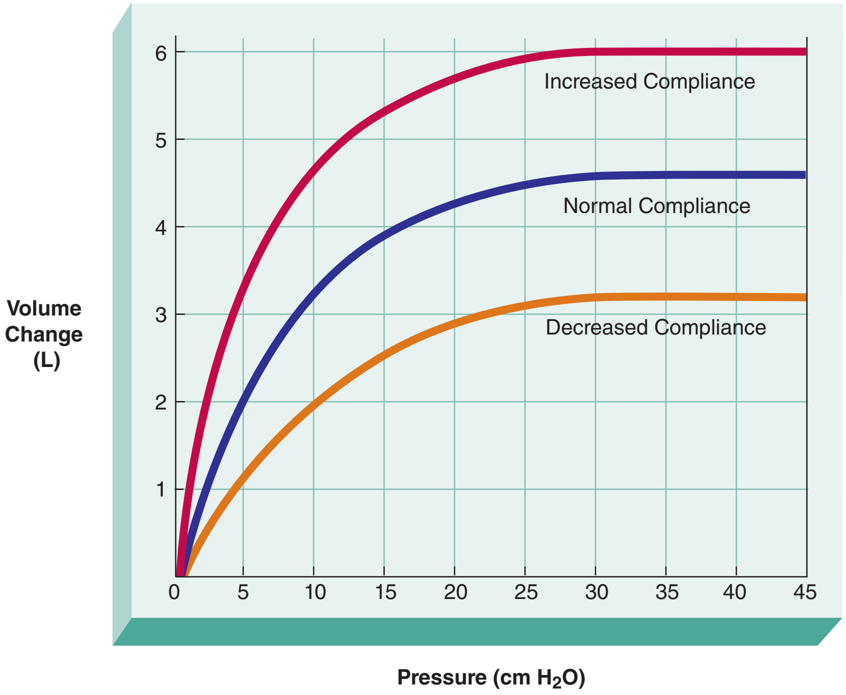
At rest, the average C_L for each breath is about 0.1 L/cm H_2O. In other words, approximately 100 mL of air is delivered into the lungs per 1-cm H_2O pressure change (see Figure 2–21). When lung compliance is increased, the lungs accept a greater volume of gas per unit of pressure change. When C_L is decreased, the lungs accept a smaller volume of gas per unit of pressure change. This relationship is also illustrated by the pressure-volume curve in Figure 2–22.

FIGURE 2-21 The pressure-volume (P-V) curve of the lungs during inspiration and expiration. Note that during inspiration, the lung compliance is initially very low, and then progressively increases in the middle of the curve, and then again progressively decreases as the lungs expand to their full capacity. For example, with a consistent pressure change of 5 cm H_20, the P-V curve shows a low lung volume changes between 10 and 15 cm H_2O (**A**), a high-volume change between 30-35 cm H_2O (**B**), and a low lung compliance with little to no volume change between 60-65 cm H_2O little to no volume change between 60-65 cm H_2O (**C**).



Note that—both in the normal and abnormal lung—C_L progressively decreases as the alveoli approach their total filling capacity. This occurs because the elastic force of the alveoli steadily increases as the lungs expand, which, in turn, reduces the ability of the lungs to accept an additional volume of gas (see Figure 2–22).

FIGURE 2-22 How changes in lung compliance affect the pressure-volume curve. When lung compliance decreases, the pressure-volume curve shifts to the right. When lung compliance increases, the pressure-volume curve shifts to the left.



Chest Wall Compliance

As discussed earlier, the chest wall has its own elastic properties, caused by the bones of the thorax and surrounding muscles. As a result, the chest wall works to offset the normal elastic properties of the lungs. If unopposed, the normal compliance of both the lungs and chest wall are about equal at 0.2 L/cm H_2O. However, because the lungs are enclosed within the thorax—and attached to the internal surface of the chest wall—the two elastic systems function as springs that naturally recoil away from each other. This action, in

Clinical Connection 2-4

Pulmonary Disorders That Force the Patient to Breathe at the Top—Flat Portion—of the Pressure-Volume Curve

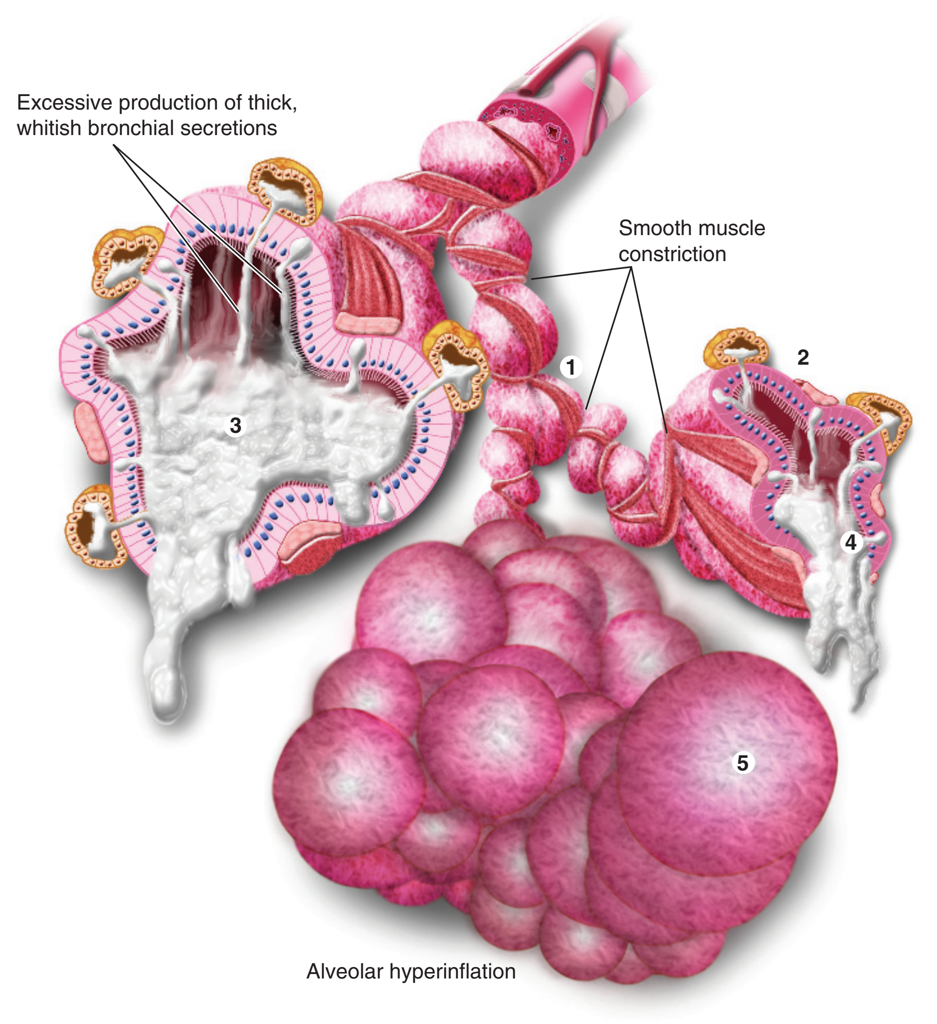
In the Clinical Application Case 2 (page 145), the respiratory therapist is called to assist in the care of a 14-year-old girl with a long history of asthma (Figure 2–23). This clinical event illustrates how an obstructive lung disorder—an acute asthma attack, in this case—can quickly cause an acute decrease in the patient's lung compliance. During an asthmatic episode, the patient's bronchial airway obstruction progressively worsens—impeding the patient's ability to fully exhale. This condition causes air trapping and hyperinflation of the lungs. Sometimes, the respiratory therapist can see this plotted on the pressure-volume curve, which shows that as the lungs become overinflated, the patient's lung compliance moves to the top—upper right-hand portion—of the pressure-volume curve—that is, the flat, very low compliant, part of the curve.

Clinical Connection 2-4, Continued

When ventilating on this portion of the volume–pressure curve, the work of breathing is very high. In this case, the patient is forced to generate high intrapleural pressure changes—with little, or no, volume change. This can be an extremely frightening experience for any patient! In addition to asthma, common obstructive lung disorders that can cause air trapping, overinflation, and decreased lung compliance—because the patient is forced to breathe on the very top, flat part of the pressure-volume curve—also include cystic fibrosis (see Figure 1–28), chronic bronchitis (see Figure 2–49), and emphysema (see Figure 2–44).

To personally experience how a patient may feel during an asthma attack, try this activity: inhale as deep as possible—that is, to the very top of the pressure-volume curve—and then attempt to breathe in and out normally without fully exhaling. Can you feel how hard it is to inhale once your lungs are fully inflated? How long do you think you could breathe at this level of your pressure-volume curve? As a respiratory therapist, you will be treating many patients who have had this experience with every acute asthmatic episode.

FIGURE 2-23 Asthma is characterized by periodic episodes of (1) reversible bronchial smooth muscle constriction, called bronchospasm; (2) airways inflammation, which results in mucosal edema and airways swelling; (3) excessive production of thick, whitish bronchial secretions; (4) mucous plugging; and (5) air trapping and hyperinflation of the alveoli.


Excessive production of thick, whitish bronchial secretions
Smooth muscle constriction
1
2
3
4
5
Alveolar hyperinflation

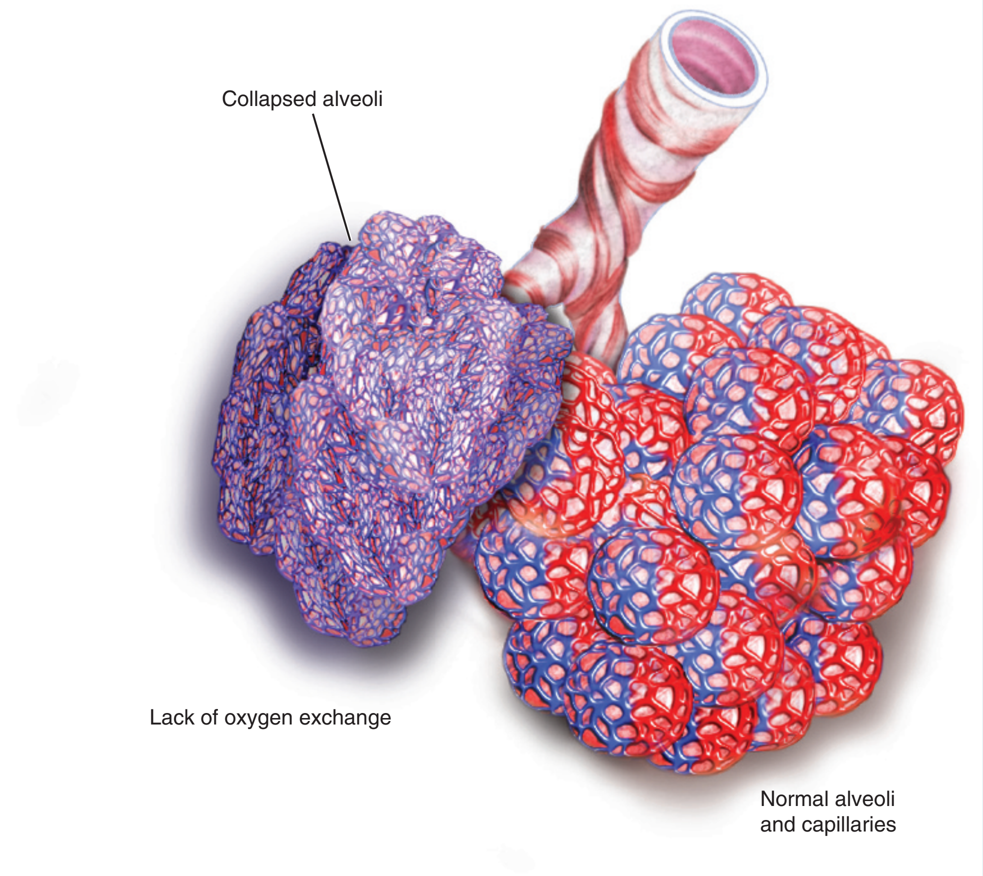
Clinical Connection 2-5

Pulmonary Disorders That Shift the Pressure—Volume Curve to the Right

Clinical Application Case 1 (page 144) describes how a chest trauma can rapidly cause an acute decrease in lung compliance. As a result of multiple broken ribs over the right anterior chest, the patient's chest moves inward during each inspiration—that is, the patient had a flail chest (see Figure 2–19 and Figure 2–20). As a result, the alveoli of the lung collapse—a condition called alveolar atelectasis (Figure 2–24). This is a restrictive lung disorder.

When plotted on a pressure-volume curve, it can be seen that as the lungs progressively collapse, the patient's pressure-volume curve quickly shifts to the right—lung compliance decreases. This condition forces the patient to generate high intrapleural pressure changes—with little or no volume change—and the work of breathing increases. A flail chest can be extremely frightening for any patient! Other restrictive lung disorders that can cause the pressure-volume curve to shift to the right include pneumonia, pneumothorax, pleural effusion, acute respiratory distress syndrome, pulmonary edema, and interstitial lung disease.

FIGURE 2-24 Atelectasis. Pathology includes the partial or total collapse of previously expanded alveoli, which result in (1) the prevention of respiratory exchange of carbon dioxide and oxygen in that part of the lung and (2) reduced lung compliance.



turn, decreases the compliance of each elastic system to about one-half of the individual components—or 0.1 L/cm H_2O. In other words, the normal lung compliance of 0.1 L/H_2O is actually the end result of the "combined" chest wall compliance and lung compliance.

Under normal conditions, the lungs and chest wall recoil to a resting volume, the functional residual capacity (FRC).[3] When the normal lung–chest wall relationship is disrupted, the chest wall tend to expand to a volume greater than the FRC, and the lungs tend to collapse to a volume less than the FRC. This lung–chest wall relationship has many clinical implications. For example, pulmonary disorders that decrease a patient's lung compliance (e.g., pneumonia, atelectasis, or acute respiratory distress syndrome) not only hinder the patient's lung expansion but also significantly decrease the patient's chest wall expansion. On the other hand, a pulmonary disorder that causes the lungs to break away from the chest wall (e.g., pneumothorax) can result in an overexpansion of the chest wall on the affected side (see Clinical Connection 2–6 and Figure 2–28 later in this chapter).

Hooke's Law

Hooke's law provides another way to explain compliance by describing the physical properties of an elastic substance. **Elastance** is the natural ability of matter to respond directly to force and to return to its original resting position or shape after the external force no longer exists. In pulmonary physiology, elastance is defined as the change in pressure per change in volume:

$$\text{Elastance} = \frac{\Delta P}{\Delta V}$$

Elastance is the reciprocal (opposite) of compliance. Thus, lungs with high compliance (greater ease of filling) have low elastance; lungs with low compliance (lower ease of filling) have high elastance. Note that elastance is the reciprocal of compliance for only a truly elastic body. Because the normal lung–chest wall is not a total, or absolute, elastic mechanism, it functions in a more *sigmoidal* than *linear* manner. Regardless of this point, it is still a satisfactory and practical approximation. Also, because of the viscous nature of the lungs and thorax, a mild degree of *hysteresis* is demonstrated on the pressure-volume curves when comparing inspiration to expiration (see Figure 2–37 later in this chapter).

Hooke's law states that when a truly elastic body, like a spring, is acted on by 1 unit of force, the elastic body will stretch 1 unit of length, and when acted on by 2 units of force it will stretch 2 units of length, and so forth. This phenomenon is only true, however, within the elastic body's normal functional range. When the force exceeds the elastic limits of the substance, the ability of length to increase in response to force rapidly decreases. Should the force continue to rise, the elastic substance will ultimately break (Figure 2–25).

When Hooke's law is applied to the elastic properties of the lungs, *volume* is substituted for *length,* and *pressure* is substituted for *force.* Thus, over the normal physiologic range of the lungs, volume varies directly with pressure. The lungs behave in a manner similar to the spring, and once the elastic limits of the lung unit are reached, little or no volume change occurs in response to pressure changes. Should the change in pressure continue to rise, the elastic limits are exceeded and the lung unit will rupture (Figure 2–26).

Clinically, this phenomenon explains a hazard associated with mechanical ventilation. That is, if the pressure during mechanical ventilation (positive-pressure breath) causes the lung unit to expand beyond its elastic capability, the lung unit could rupture, allowing alveolar gas to move into the pleural space, and thus causing the lungs to collapse. This condition is called a **tension pneumothorax** (see Figure 2–28).

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[3] Read more on the functional residual capacity in Chapter 3.

FIGURE 2-25 Hooke's law. When a truly elastic body—such as the spring in this illustration—is acted on by 1 unit of force, the elastic body will stretch 1 unit of length; when acted on by 2 units of force, it will stretch 2 units of length; and so forth. When the force goes beyond the elastic limit of the substance, however, the ability of length to increase in response to force quickly ceases.

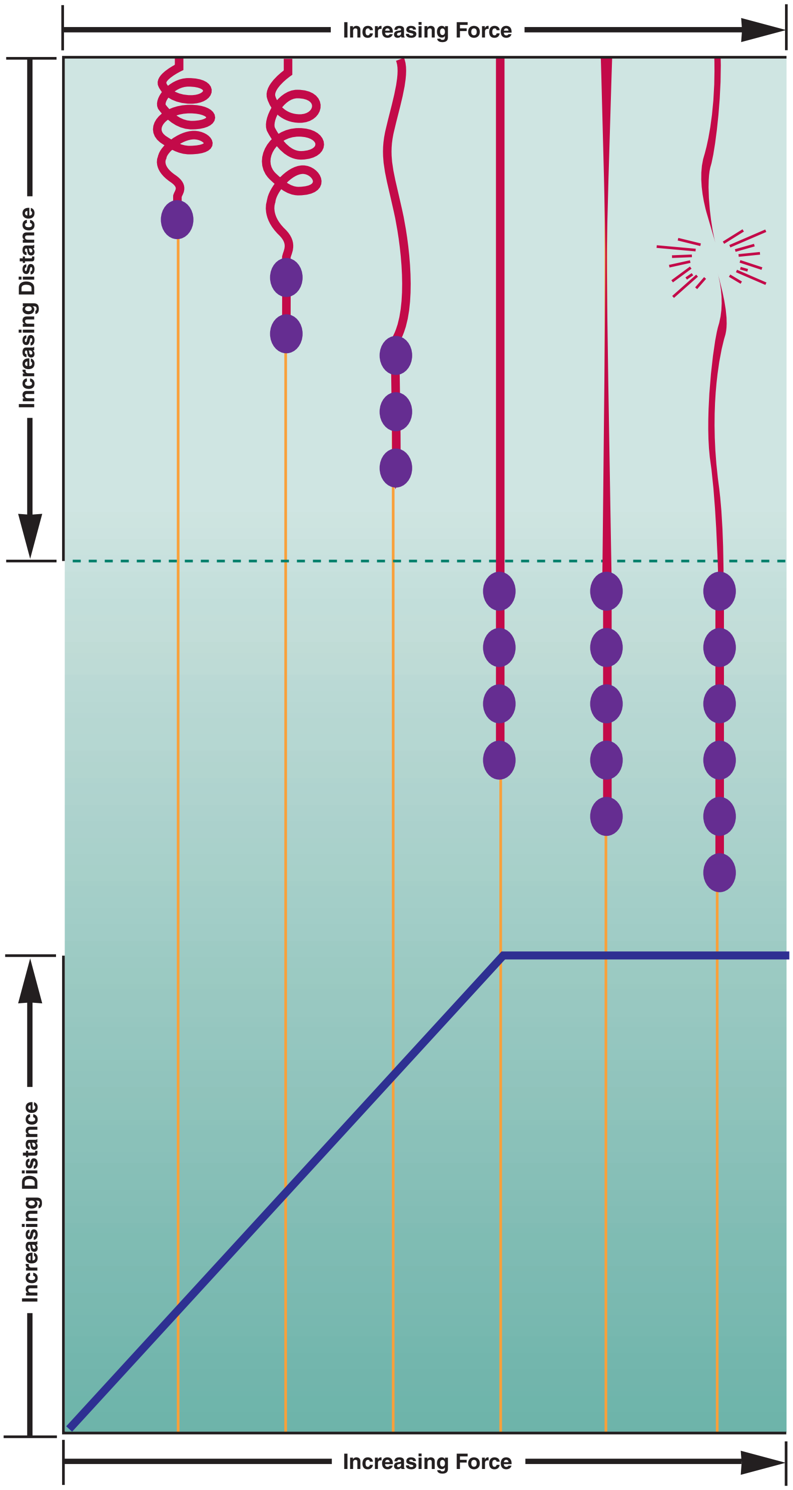
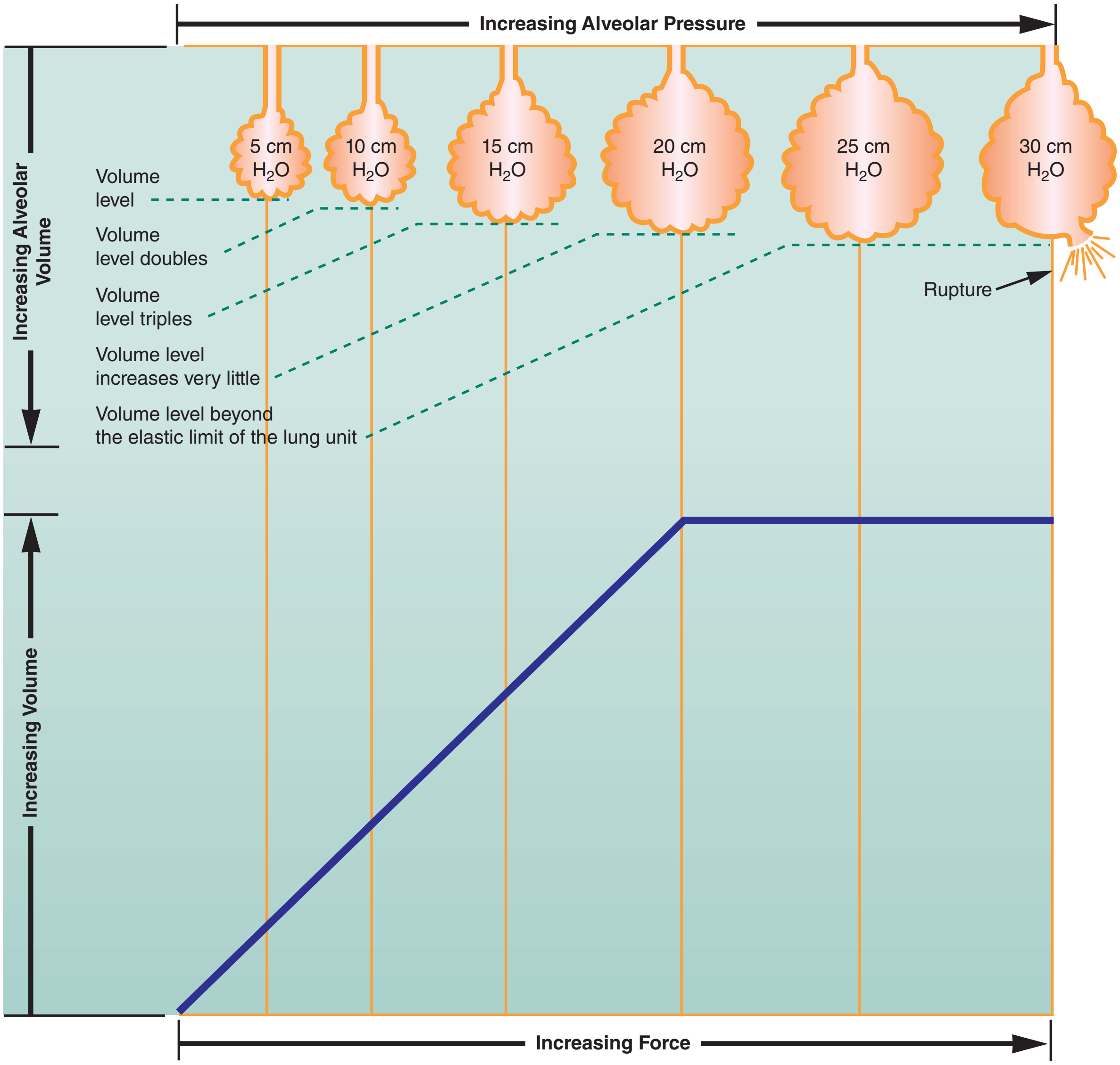

Increasing Force
Increasing Distance
Increasing Distance
Increasing Force

FIGURE 2-26 Hooke's law applied to the elastic properties of the lungs. Over the physiologic range, volume changes vary directly with pressure changes. Once the elastic limits are reached, however, little or no volume change occurs in response to pressure change.



Clinical Connection 2-6

Positive-Pressure Ventilation

Clinically, when the patient is placed on a positive-pressure ventilator, the intrapleural pressures, intra-alveolar pressures, and the movement of the diaphragm will all be quite different than the normal mechanisms of pulmonary ventilation.

Inspiratory Phase of Positive-Pressure Ventilation

Figure 2–27A shows that when the patient receives a positive-pressure breath from a mechanical ventilator, the intra-alveolar pressure progressively rises above atmospheric pressure—similar to the positive

Continued

Clinical Connection 2-6, Continued

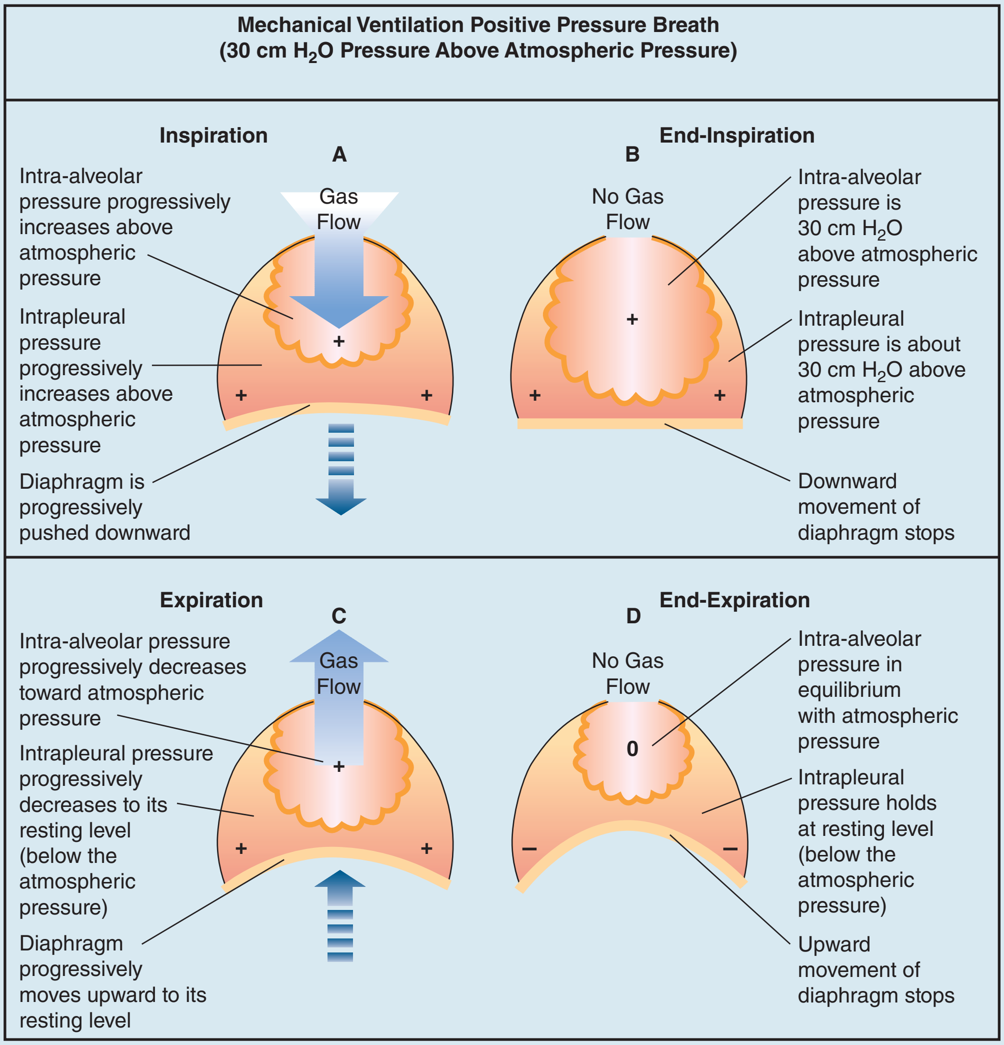
pressure generated in an elastic balloon as it is being inflated. For example, if the mechanical ventilator delivered 30 cm H_2O pressure to the patient's lung during inspiration, the intra-alveolar pressure would increase to about 30 cm H_2O above the atmospheric pressure at the end of inspiration. As the pressure progressively increases in the alveoli during inspiration, the intrapleural pressure also increases.

As shown in Figure 2–27, the intrapleural pressure would gradually increase to about 30 cm H_2O above its normal resting level, which, as illustrated in Figure 2–11, is normally below atmospheric pressure. Finally, as the intra-alveolar and intrapleural pressure increase during a positive-pressure breath, the lungs expand, pushing the diaphragm downward. This process continues until the positive-pressure breath stops (Figure 2–27B).

Expiratory Phase of Positive-Pressure Ventilation

During exhalation, the intra-alveolar pressure decreases toward atmospheric pressure and allows the elastic properties of the lungs to return to their normal resting level—similar to the decreased positive pressure that occurs in an elastic balloon that

FIGURE 2-27 How a positive pressure breath from a mechanical ventilator affects the intra-alveolar pressure, intrapleural pressure, the excursion of the diaphragm, and gas flow during inspiration and expiration.


Mechanical Ventilation Positive Pressure Breath
(30 cm H_2O Pressure Above Atmospheric Pressure)
Inspiration
A
Intra-alveolar pressure progressively increases above atmospheric pressure
Gas Flow
+
Intrapleural pressure progressively increases above atmospheric pressure
+
+
Diaphragm is progressively pushed downward
End-Inspiration
B
No Gas Flow
Intra-alveolar pressure is 30 cm H_2O above atmospheric pressure
+
Intrapleural pressure is about 30 cm H_2O above atmospheric pressure
+
+
Downward movement of diaphragm stops
Expiration
C
Intra-alveolar pressure progressively decreases toward atmospheric pressure
Gas Flow
+
Intrapleural pressure progressively decreases to its resting level (below the atmospheric pressure)
+
+
Diaphragm progressively moves upward to its resting level
End-Expiration
D
No Gas Flow
Intra-alveolar pressure in equilibrium with atmospheric pressure
0
Intrapleural pressure holds at resting level (below the atmospheric pressure)
–
–
Upward movement of diaphragm stops

Clinical Connection 2-6, Continued

is being allowed to return to the atmospheric pressure during deflation. This means that the high intra-alveolar pressure moves in the direction of the low atmospheric pressure until the intra-alveolar pressure is in equilibrium with the atmospheric pressure. As the intra-alveolar pressure returns to normal, the intrapleural pressure decreases to its resting level (below the atmospheric pressure), and the diaphragm moves upward to its resting level (Figure 2–27C).

At end-expiration, the intra-alveolar pressure is in equilibrium with atmospheric pressure. The intrapleural pressure is held at its resting level that, under normal circumstances, is below atmospheric pressure. The upward movement of the diaphragm stops at end-expiration (Figure 2-27D). The administration of positive-pressure ventilation may also cause a number of adverse side effects, including lung rupture and gas accumulation between the lungs and chest wall (tension pneumothorax) and decreased cardiac output and blood pressure (see Clinical Connection 2–7).

Clinical Connection 2-7

Hazards of Positive-Pressure Ventilation

The respiratory therapist must carefully monitor the patient on mechanical ventilation for a number of adverse effects associated with positive-pressure ventilation—including a sudden tension pneumothorax and decreased cardiac output and blood pressure.

Tension Pneumothorax

A patient receiving high positive pressures during mechanical ventilation is always at some degree of risk of a sudden lung rupture and resulting pneumothorax. A pneumothorax in which the intrapleural pressure is greater than the intra-alveolar (or atmospheric) pressure is called a **tension pneumothorax**. At the bedside, a number of clinical signs and symptoms can develop that indicate a sudden tension pneumothorax: (1) increased heart rate, (2) diminished or absent breath sounds on the affected side, (3) hyperresonant percussion note over the pneumothorax, (4) tracheal shift to the unaffected side, (5) displaced heart sounds, (6) an enlarged and immobile chest on the affected side, and (7) decreased cardiac output and blood pressure. A chest X-ray is used to confirm the extent of a pneumothorax and typically reveals (1) gas accumulation in the pleural cavity, (2) depressed diaphragm, and (3) shift of the mediastinum to the unaffected side of the chest.

The treatment for a pneumothorax is the insertion of a chest tube into the intrapleural space and the application of suction to draw out the air and re-expand the lung. Figure 2–28A illustrates a right-sided tension pneumothorax. Figure 2-28B shows a chest X-ray of a right-sided tension pneumothorax. Note the collapsed right lung, the depressed right diaphragm, and the heart and mediastinum pushed to the unaffected side.

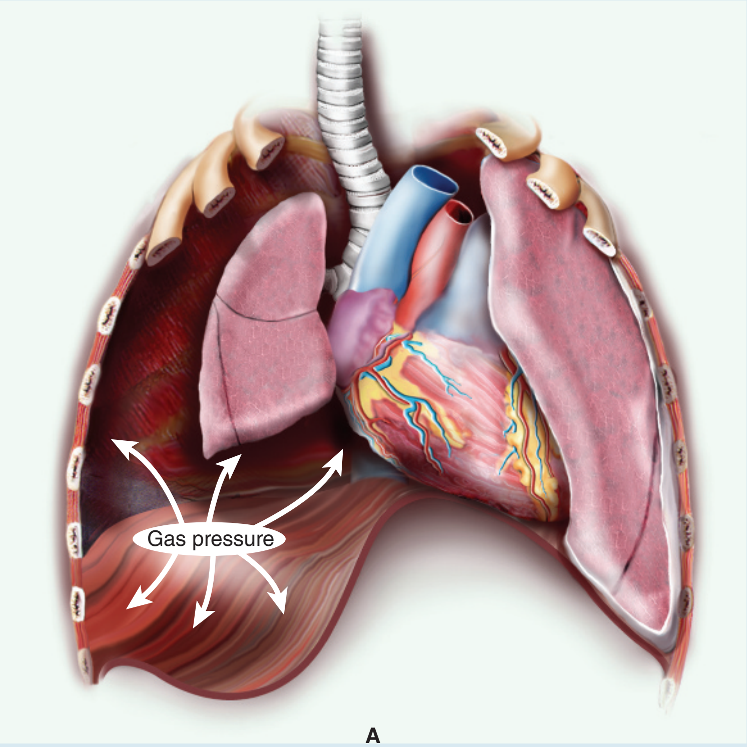
Decreased Cardiac Output and Blood Pressure

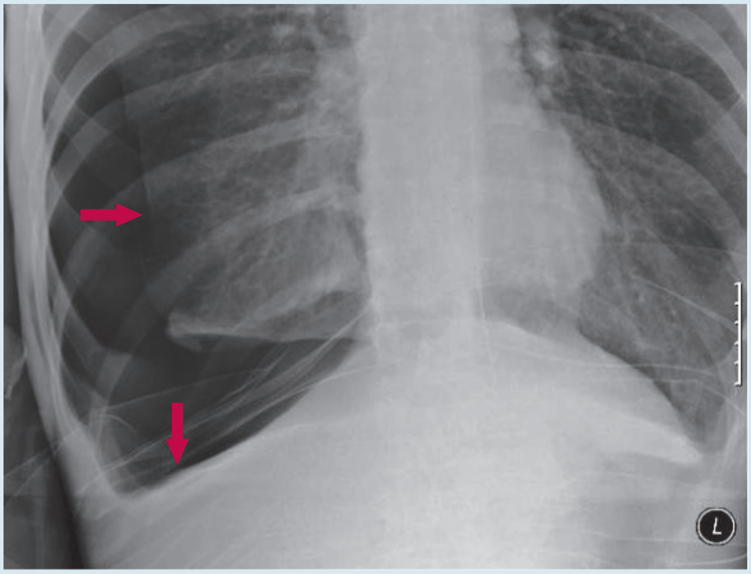
The decreased cardiac output and blood pressure associated with a tension pneumothorax are caused by the **positive intrapleural pressure**—which is caused by the gas accumulation in the pleural cavity. As a result of the positive pleural pressure, the major intrathoracic veins—the inferior and superior vena cava—are compressed. This action impedes venous return to the heart. In general, the more severe the tension pneumothorax, (1) the greater the positive pressure in the pleural cavity, (2) the more the major intrathoracic veins will be compressed, and (3) the more cardiac output will be reduced. Because of the high resistance encountered by blood returning to the right atrium of the heart, blood pooling develops in the peripheral vascular system—mainly the legs, arms, and abdominal viscera.

Continued

Clinical Connection 2-7, Continued

FIGURE 2-28 **A.** Illustration of a right-sided tension pneumothorax. **B.** Chest X-ray of a right-sided tension pneumothorax caused by positive pressure ventilation. Note, in both A and B, the collapsed right lung (horizontal arrow in B), the depressed right diaphragm (vertical arrow in B), and the heart and mediastinum pushed to the unaffected side (i.e., pushed to the patient's left side).





Courtesy T. Des Jardins, WindMist LLC

Surface Tension and Its Effect on Lung Expansion

In addition to the elastic properties of the lungs, the fluid (primarily H_2O) that lines the inner surface of the alveoli can profoundly resist lung expansion. To understand how the liquid coating the intra-alveolar surface can affect lung expansion, an understanding of the following is essential: (1) surface tension, (2) Laplace's law, and (3) how the substance called pulmonary surfactant offsets alveolar surface tension.

Clinical Connection 2-8

Negative-Pressure Ventilation

In 1928, Drinker and Shaw invented the first modern and practical negative-pressure ventilator—most commonly known as the "iron lung."[4] This early prototype negative-pressure ventilator consisted of an iron box and two vacuum cleaners. During the next few years, John H. Emerson developed a more cost-effective, commercial version of the iron lung. The iron lung was made famous for its important contributions during the poliomyelitis epidemics of the 1930s and 1950s. In general, the iron lung is a large elongated tank that encases the patient's body up to the neck. The neck is sealed with a rubber gasket so that only the patient's head is exposed to the atmosphere (i.e., barometric pressure).

To activate an **inspiration**, the iron lung uses a piston, pump-like mechanism that generates a negative pressure (vacuum) around the patient's chest, which, in turn, causes the thorax and lungs to expand (increased volume). This action causes the intra-alveolar pressure to decrease—remember, according to Boyle's law, as pressure deceases, the volume increases. Because the atmospheric pressure is higher than the intra-alveolar pressure—that is, a pressure gradient exists—gas from the atmosphere moves through the patient's nose or mouth to the alveoli (Figure 2–29A).

This gas flow continues until the intra-alveolar pressure and the atmospheric pressures are in equilibrium. Once the equilibrium point is reached, gas flow stops. This period of no gas flow is the **end-inspiration** phase of the negative-pressure ventilation cycle (Figure 2–29B).

To initiate **expiration**, the piston mechanism releases the negative pressure, which, in turn, allows the elastic recoil forces of the thorax and lungs to return to their normal—and smaller—size (decreased volume). This action causes the intra-alveolar pressure to increase, creating a pressure gradient between the intra-alveolar pressure and atmospheric pressure. Because the intra-alveolar pressure is higher than the atmospheric pressure, gas from the alveoli moves through the tracheobronchial tree to the atmosphere (Figure 2–29C).

This gas flow will continue until the intra-alveolar pressure and the atmospheric pressure are in equilibrium. Once the equilibrium point is reached, gas flow stops. This period of no gas flow is the **end-expiration** phase of the negative-pressure ventilation cycle (Figure 2–29D).

There are several disadvantages associated with the full-body iron lung, including (1) patient access, (2) abdominal venous blood pooling, (3) decreased venous return, and (4) decreased cardiac output and blood pressure. Although the iron lung is still being utilized for long-term ventilation today, the prominent negative-pressure devices used are (1) the Porta-lung (offers the same level of efficiency as the iron lung, but in a lightweight portable unit), (2) the chest cuirass (an upper body only shell—named after the body armor worn by medieval soldiers), or (3) the body suit.

Continued

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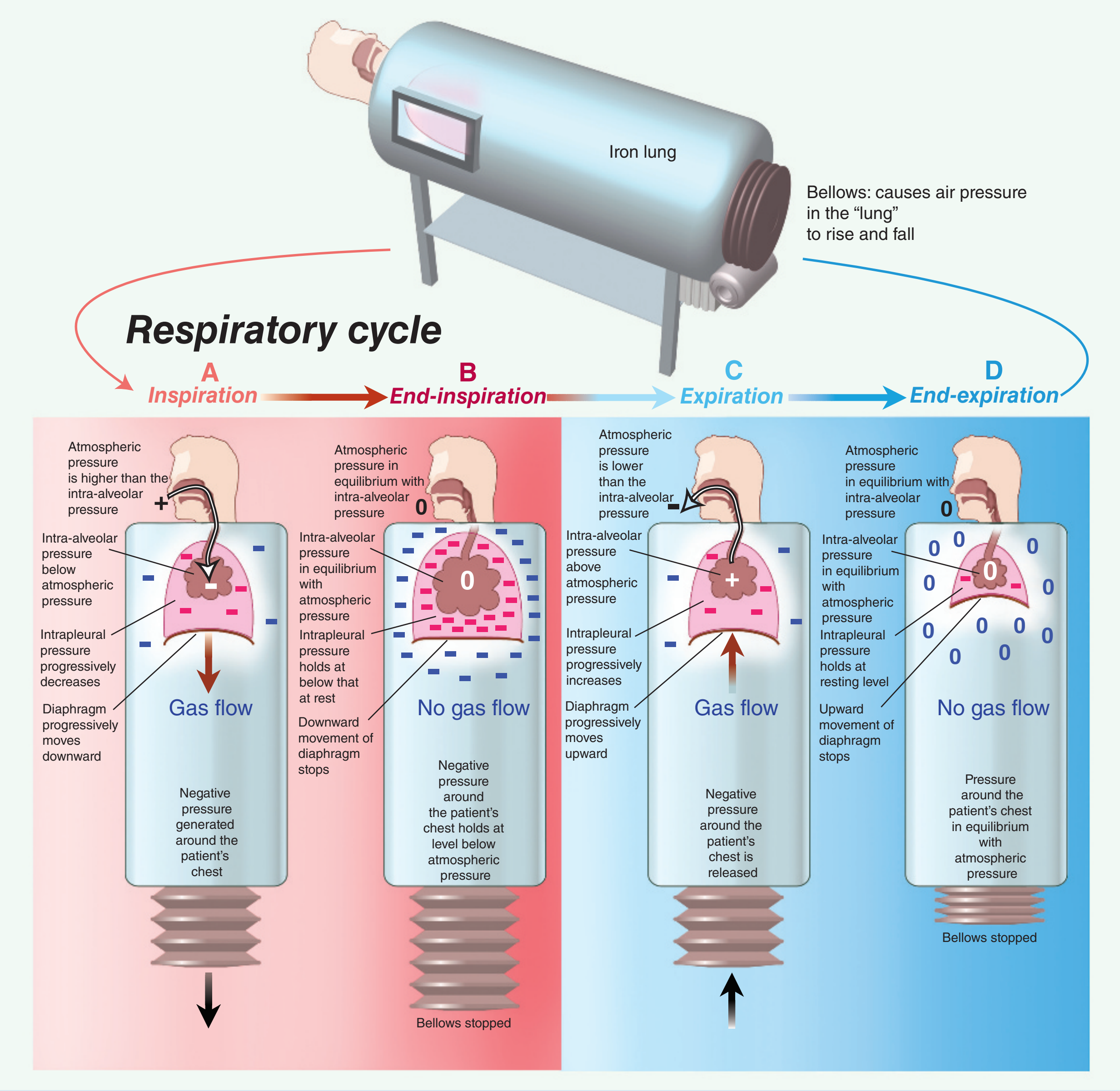
[4] Also called the Drinker tank or Shaw tank.

Clinical Connection 2-8, Continued

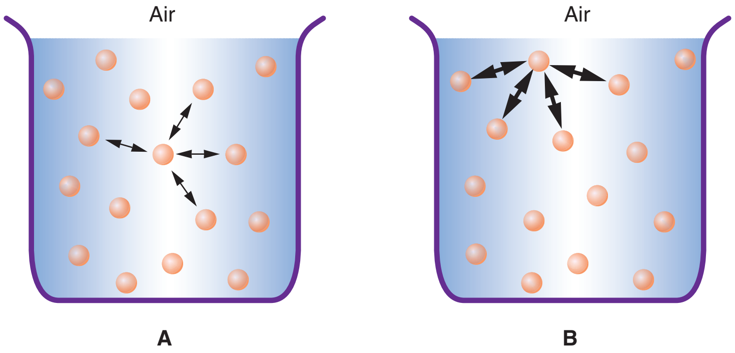
FIGURE 2-29 How a negative pressure breath from a mechanical ventilator affects the intra-alveolar pressure, pleural pressure, and the excursion of the diaphragm, and gas flow during inspiration and expiration.


Iron lung
Bellows: causes air pressure in the "lung" to rise and fall
Respiratory cycle
A Inspiration
B End-inspiration
C Expiration
D End-expiration
Atmospheric pressure is higher than the intra-alveolar pressure
+
Intra-alveolar pressure below atmospheric pressure
-
Intrapleural pressure progressively decreases
Diaphragm progressively moves downward
Gas flow
Negative pressure generated around the patient's chest
Atmospheric pressure in equilibrium with intra-alveolar pressure
0
Intra-alveolar pressure in equilibrium with atmospheric pressure
0
Intrapleural pressure holds at below that at rest
Downward movement of diaphragm stops
No gas flow
Negative pressure around the patient's chest holds at level below atmospheric pressure
Bellows stopped
Atmospheric pressure is lower than the intra-alveolar pressure
-
Intra-alveolar pressure above atmospheric pressure
+
Intrapleural pressure progressively increases
Diaphragm progressively moves upward
Gas flow
Negative pressure around the patient's chest is released
Atmospheric pressure in equilibrium with intra-alveolar pressure
0
Intra-alveolar pressure in equilibrium with atmospheric pressure
0
Intrapleural pressure holds at resting level
Upward movement of diaphragm stops
No gas flow
Pressure around the patient's chest in equilibrium with atmospheric pressure
Bellows stopped

Surface Tension

When liquid molecules are completely surrounded by identical molecules, the molecules are mutually attracted toward one another and, therefore, move freely in all directions (Figure 2–30A). When a liquid–gas interface exists, however, the liquid molecules at the liquid–gas interface are strongly attracted to the liquid molecules within the liquid mass (Figure 2–30B). This molecular, cohesive force at the liquid–gas interface is called *surface tension*. It is the surface tension, for example, that maintains the shape of a water droplet, or makes it possible for an insect to move or stay afloat on the surface of a pond.

FIGURE 2-30 In model A, the liquid molecules in the middle of the container are mutually attracted toward each other and, therefore, move freely in all directions. In model B, the liquid molecules near the surface (liquid–gas interface) are strongly attracted to the liquid molecules within the liquid mass. This molecular force at the liquid–gas interface is called surface tension.



Surface tension is measured in dynes per centimeter. One dyne/cm is the force necessary to cause a tear 1 cm long in the surface layer of a liquid. This is similar to using two hands to pull a thin piece of cloth apart until a split 1 cm in length is formed (1 cm H_2O pressure equals 980 dynes/cm). The liquid film that lines the interior surface of the alveoli has the potential to exert a force in excess of 70 dynes/cm, a force that can easily cause complete alveolar collapse.

Laplace's Law

Laplace's law describes how the *distending pressure* of a liquid bubble (not an alveolus) is influenced by (1) the surface tension of the bubble and (2) the size of the bubble itself. When Laplace's law is applied to a sphere with one liquid–gas interface (e.g., a bubble completely submerged in a liquid), the equation is written as follows:

$$P = \frac{2\ ST}{r}$$

where P is the pressure difference (dynes/cm^2), ST is surface tension (dynes/ cm), and r is the radius of the liquid sphere (cm); the factor 2 is required when the law is applied to a liquid sphere with one liquid–gas interface. It should be noted that when Laplace's law is arranged as shown, it also applies to the lungs. This is because the alveoli are in constant contact with each other and, therefore, only have one surface area—the intra-alveolar surface area (refer to Figure 1–40).

When the law is applied to a bubble with two liquid–gas interfaces (e.g., a soap bubble blown on the end of a tube has a liquid–gas interface both on the inside and on the outside of the bubble), the numerator contains the factor 4 rather than 2:

$$P = \frac{4\ ST}{r}$$

Laplace's law shows that the *distending pressure* of a liquid sphere is (1) directly proportional to the surface tension of the liquid and (2) inversely proportional to the radius of the sphere.

In other words, the numerator of Laplace's law shows that (1) as the surface tension of a liquid bubble increases, the distending pressure necessary to hold the bubble open increases, or (2) the opposite—when the surface tension of a liquid bubble decreases, the distending pressure of the bubble decreases (Figure 2–31). The denominator of Laplace's law shows that (1) when the size of a liquid bubble increases, the distending pressure necessary to hold the bubble open decreases, or (2) the opposite—when the size of the bubble decreases, the distending pressure of the bubble increases (Figure 2–32). Because of this interesting physical phenomenon, when two different size bubbles—having the same surface

FIGURE 2-31 Bubbles A and B are the same size. The surface tension (ST) of bubble A is 10 dynes/cm and requires a distending pressure (P) of 5 cm H_2O to maintain its size. The surface tension of bubble B is 20 dynes/cm H_2O (twice that of bubble A) and requires a distending pressure of 10 cm H_2O (twice that of bubble A) to maintain its size (r = radius).

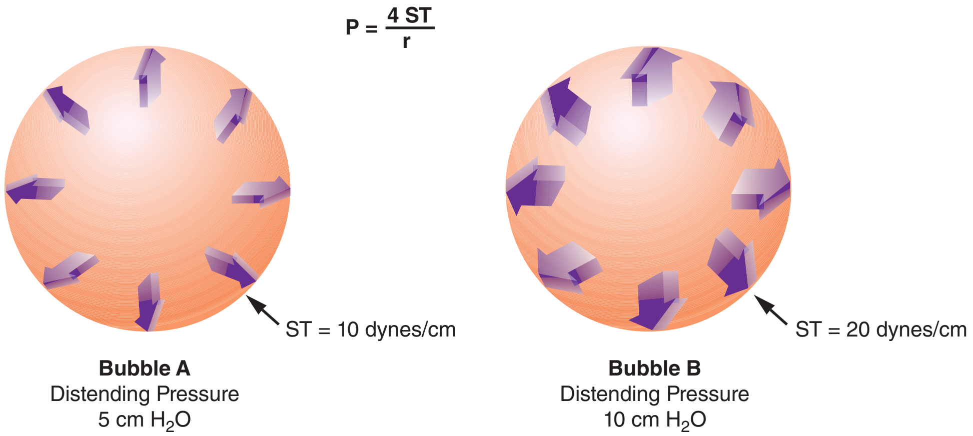
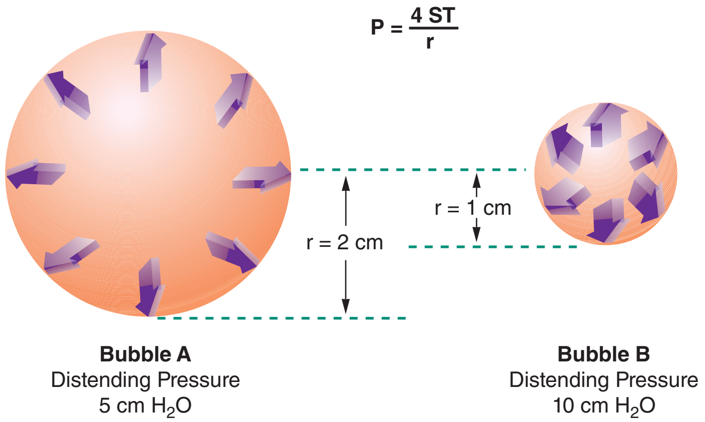

$P = \frac{4\ ST}{r}$
ST = 10 dynes/cm
ST = 20 dynes/cm
Bubble A
Distending Pressure
5 cm H_2O
Bubble B
Distending Pressure
10 cm H_2O

FIGURE 2-32 The surface tension (ST) of bubbles A and B is identical. The radius (r) of bubble A is 2 cm, and it requires a distending pressure (P) of 5 cm H_2O to maintain its size. The radius of bubble B is 1 cm (one-half that of bubble A), and it requires a distending pressure of 10 cm H_2O (twice that of bubble A) to maintain its size.


$P = \frac{4\ ST}{r}$
r = 2 cm
r = 1 cm
Bubble A
Distending Pressure
5 cm H_2O
Bubble B
Distending Pressure
10 cm H_2O

tension—are in direct communication, the greater pressure in the smaller bubble will cause the smaller bubble to empty into the larger bubble (Figure 2–33).

During the formation of a new bubble (e.g., a soap bubble blown on the end of a tube), the principles of Laplace's law do not come into effect until the distending pressure of the liquid sphere goes beyond what is called the *critical opening pressure.* As shown in Figure 2–34, the critical opening pressure is the high pressure (with little volume change) that is initially required to overcome the liquid molecular force during the formation of a new bubble—similar to the high pressure first required to blow up a new balloon. Figure 2–34 also shows that, prior to the critical opening pressure, the distending pressure must progressively increase to enlarge the size of the bubble. In other words, the distending pressure is *directly proportional* to the radius of the bubble (the opposite of what Laplace's law states).

Once the critical opening pressure is reached, however, the distending pressure progressively decreases as the bubble increases in size—the distending pressure, as described by Laplace's law, is *inversely*

FIGURE 2-33 Bubbles A and B have the same surface tension. When the two bubbles are in direct communication, the higher pressure in the smaller bubble A causes it to empty into the large bubble B.

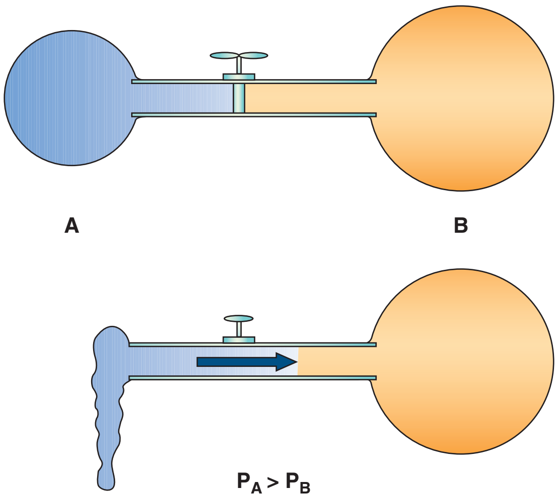
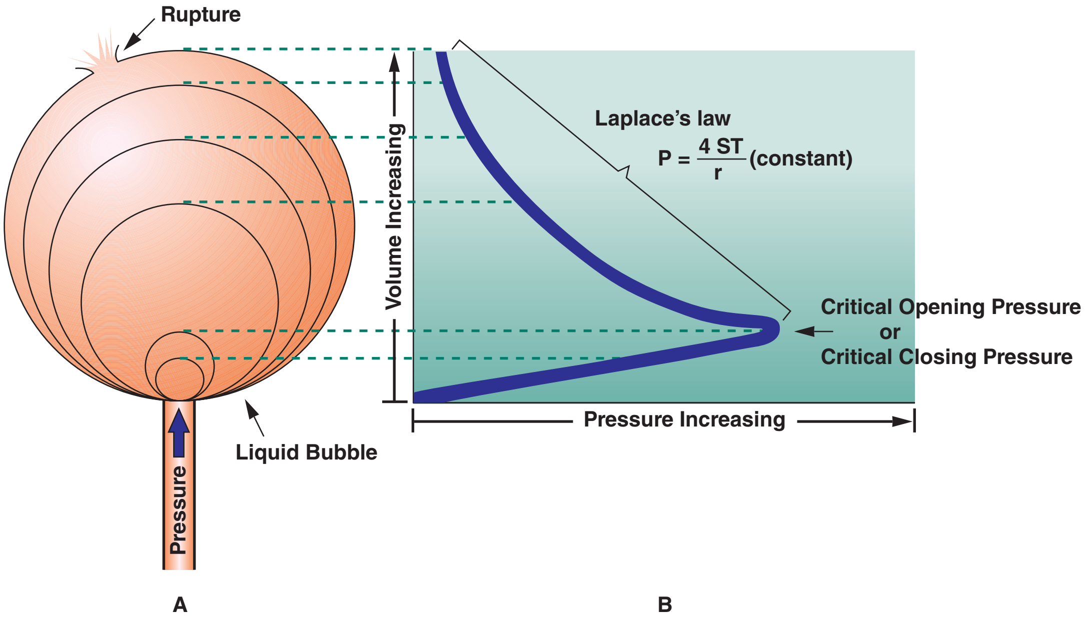


FIGURE 2-34 **A.** Model showing the formation of a new liquid bubble at the end of a tube. **B.** Graph showing the distending pressure required to maintain the bubble's size (volume) at various stages. Initially, a high pressure, providing little volume change, is required to inflate the bubble. Once the critical opening pressure (same as critical closing pressure) is reached, however, the distending pressure progressively decreases as the size of the bubble increases. Thus, between the critical opening pressure and the point at which the bubble ruptures, the bubble behaves according to Laplace's law. Laplace's law applies to the normal functional size range of the bubble.



proportional to the radius of the bubble. The distending pressure will continue to decrease until the bubble enlarges to its breaking point and ruptures. It is interesting to note that just before the bubble breaks, the distending pressure is at its lowest level (see Figure 2–34).

Conversely, Laplace's law shows that as an inflated bubble decreases in size, the distending pressure proportionally increases until the pressure reaches what is called the *critical closing pressure* (actually the same pressure as the critical opening pressure). When the size of the bubble decreases beyond this point, the liquid molecular force of the bubble becomes greater than the distending pressure and the bubble collapses (see Figure 2–34).

It should be emphasized that *Laplace's law does not state that the surface tension varies with the size of the bubble.* To the contrary, the law shows that as a liquid bubble changes in size, it is the *distending pressure—not the surface tension*—that varies inversely with the radius. In fact, as the radius of the sphere increases, the surface tension remains the same until the size of the bubble goes beyond its natural elastic limit and ruptures.

The fact that the surface tension remains the same while the radius of a liquid sphere changes can be illustrated mathematically by rearranging Laplace's law as follows:

1. Because surface tension is a property of the fluid and is constant for any specific fluid, Laplace's law can be restated as:

   $$P = \frac{k}{r}$$

   where k is a constant (in this case, the constant k equals surface tension) and P (pressure) is inversely proportional to r (radius).
2. The equation $P = k \div r$ can be rearranged as follows:

   $$Pr = k$$

   The formula now shows that the variable quantities (Pr) are inversely proportional and that their product is a constant (k). Thus, as one variable increases, the other must decrease to maintain a constant product (k).

   To demonstrate this concept, consider taking a 400-mile automobile trip. With the formula distance = rate × time ($d = rt$), which represents product (d) and variable quantities (rt), we have:

   $$400 = rt \ (d = 400 \text{ miles})$$

   or

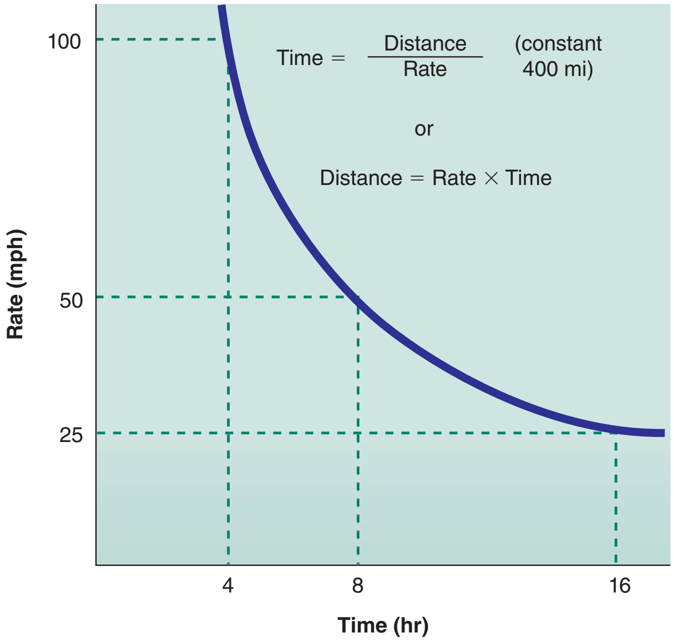
   $$\frac{400}{r} = t$$

   On such a trip, assume that we travel at 50 miles per hour (mph) and that the trip takes 8 hours ($400 \div 50 = 8$). If we travel by train and increase the speed to 100 mph, the time of the trip decreases to 4 hours. If, however, we decrease the speed to 25 mph, the time increases to 16 hours ($400 \div 25 = 16$). In other words, as the speed increases the time decreases and vice versa, but the product (d) remains a constant 400 miles, which is determined by the length of the trip.
3. Thus, when two variables are inversely proportional, such as $rt = 400$ or $t = 400 \div r$, the time increases as the rate decreases, and time decreases as the rate increases (Figure 2–35). Note the similarity of the graph in Figure 2–35 to the portion of the graph that represents Laplace's law in Figure 2–34B.

Laplace's Law Applied to the Alveolar Fluid Lining

Because the liquid film that lines the alveolus resembles a bubble or sphere, according to Laplace's law, when the alveolar fluid is permitted to behave according to its natural tendency, a high transpulmonary pressure must be generated to keep the small alveoli open (see Figure 2–34). Fortunately, in the healthy lung, the natural tendency for the smaller alveoli to collapse is offset by a fascinating substance called pulmonary surfactant.

FIGURE 2-35 Rate and time are inversely proportional (as rate increases, time decreases; and as rate decreases, time increases).



How Pulmonary Surfactant Regulates Alveolar Surface Tension

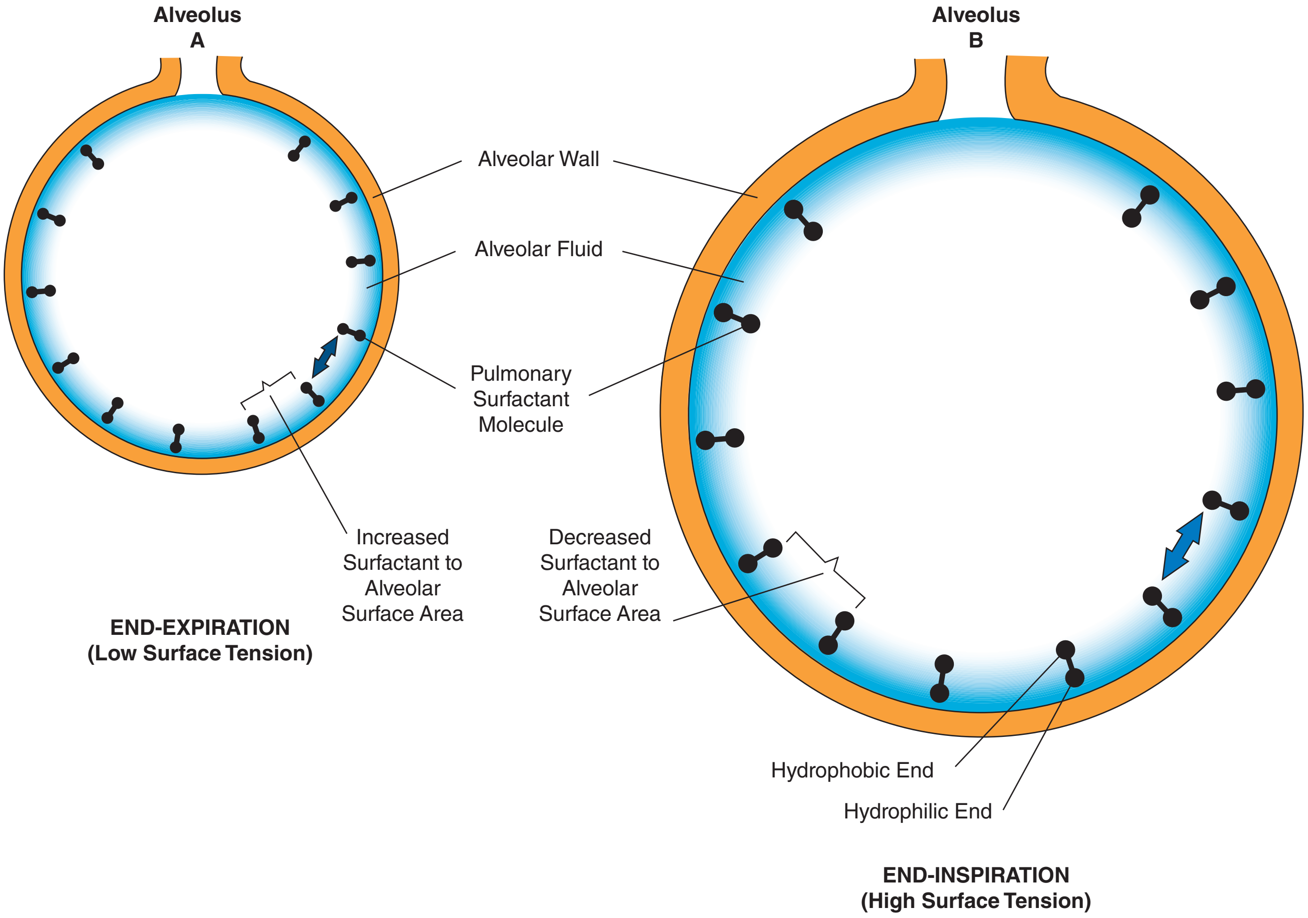
Pulmonary surfactant is an important and complex substance that is produced and stored in the alveolar type II cells (see Figure 1–30). It is composed of **phospholipids** (about 90 percent) and **protein** (about 10 percent). The primary surface tension-lowering chemical in pulmonary surfactant is the phospholipid **dipalmitoyl phosphatidylcholine (DPPC)**. The DPPC molecule has both a *hydrophobic* (water-insoluble) end and a *hydrophilic* (water-soluble) end. This unique hydrophobic/hydrophilic structure causes the DPPC molecule to position itself at the alveolar gas–liquid interface so that the hydrophilic end is toward the liquid phase and the hydrophobic end is toward the gas phase. Pulmonary surfactant at the alveolar liquid–gas interface can profoundly lower alveolar surface tension.

The DPPC molecule at the alveolar gas–liquid interface causes surface tension to decrease in proportion to its ratio to alveolar surface area. That is, when the alveolus decreases in size (exhalation), the proportion of DPPC to the alveolar surface area increases. This, in turn, increases the effect of the DPPC molecules and causes the alveolar surface tension to decrease (Figure 2–36A).

In contrast, when the alveolus increases in size (inhalation), the relative amount of DPPC to the alveolar surface area decreases (because the number of surfactant molecules does not change when the size of the alveolus changes), which decreases the effect of the DPPC molecules and causes the alveolar surface tension to increase (Figure 2–36B). In fact, as the alveolus enlarges, the surface tension will progressively increase to the value it would naturally have in the absence of pulmonary surfactant. Clinically, however, the fact that surface tension increases as the alveolus enlarges is not significant because according to Laplace's law, the distending pressure required to maintain the size of a bubble progressively decreases as the size of the bubble increases (see Figure 2–34).

It is estimated that the surface tension of the average alveolus varies from 5 to 15 dynes/cm (when the alveolus is very small) to about 50 dynes/cm (when the alveolus is fully distended) (Figure 2–37). Because pulmonary surfactant has the ability to reduce the surface tension of the small alveoli, the high

FIGURE 2-36 **A.** In the normal lung, the surface tension is low in the small alveolus because the ratio of surfactant to alveolar surface is high. **B.** As the alveolus enlarges, the surface tension steadily increases because the ratio of surfactant to alveolar surface decreases.


Alveolus
A
Alveolus
B
Alveolar Wall
Alveolar Fluid
Pulmonary Surfactant Molecule
Increased Surfactant to Alveolar Surface Area
Decreased Surfactant to Alveolar Surface Area
END-EXPIRATION (Low Surface Tension)
Hydrophobic End
Hydrophilic End
END-INSPIRATION (High Surface Tension)

distending pressure that would otherwise be required to offset the critical closing pressure of the small alveoli is virtually eliminated.

In the absence of pulmonary surfactant, however, the alveolar surface tension increases to the level it would naturally have (50 dynes/cm), and the distending pressure necessary to overcome the recoil forces of the liquid film coating the small alveoli is high. In short, the distending pressure required to offset the recoil force of the alveolar fluid behaves according to Laplace's law. As a result, when the distending pressure of the small alveoli falls below the critical closing pressure, the liquid molecular force pulls the alveolar walls together (see Figure 2–34). Once the liquid walls of the alveolus come into contact with one another, a liquid bond develops that strongly resists the re-expansion of the alveolus. Complete alveolar collapse is called **atelectasis**.

Table 2–1 lists some respiratory disorders that cause pulmonary surfactant deficiency.

Summary of the Elastic Properties of the Lungs

There are two major elastic forces in the lungs that cause an inflated lung to recoil inward: the elastic properties of the lungs and the surface tension of the liquid film that lines the alveoli.

FIGURE 2-37 In the normal lung, the surface tension force progressively increases as the alveolar size increases. Similarly, as the alveolar size decreases, the surface tension force progressively decreases. Note that because of the alveolar surface tension, the actual physical change of the alveolus lags behind the pressure applied to it. When such a phenomenon occurs in the field of physics (i.e., a physical manifestation lagging behind a force), a hysteresis is said to exist. When this lung characteristic is plotted on a pressure-volume curve, the alveolus is shown to deflate along a different curve than that inscribed during inspiration and the curve has a looplike appearance. The hysteresis loop shows graphically that at any given pressure the alveolar volume is less during inspiration than it is during expiration. This alveolar hysteresis is virtually eliminated when the lungs are inflated experimentally with saline; such an experimental procedure removes the alveolar liquid–gas interface and, therefore, the alveolar surface tension. Inspiratory capacity is the volume of air that can be inhaled after a normal exhalation. Functional residual capacity is the volume of air remaining in the lungs after a normal exhalation.

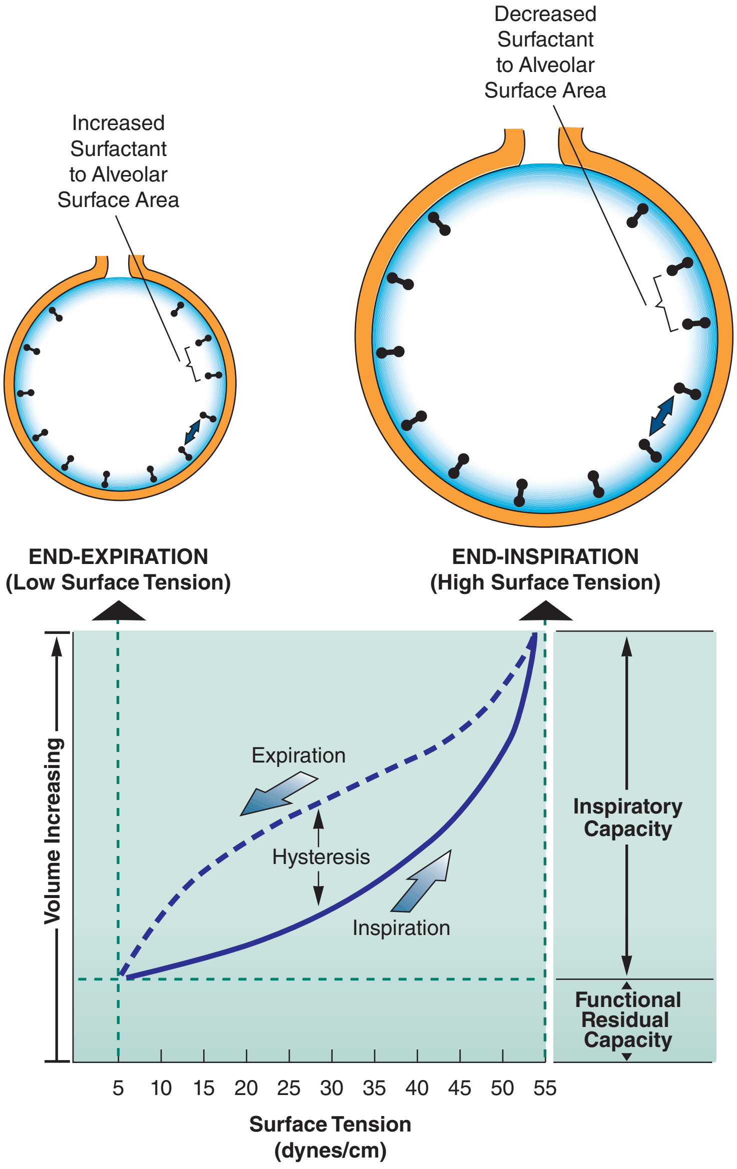

Increased Surfactant to Alveolar Surface Area
Decreased Surfactant to Alveolar Surface Area
END-EXPIRATION (Low Surface Tension)
END-INSPIRATION (High Surface Tension)
Volume Increasing
Expiration
Hysteresis
Inspiration
Inspiratory Capacity
Functional Residual Capacity
5 10 15 20 25 30 35 40 45 50 55
Surface Tension (dynes/cm)

TABLE 2-1 Causes of Pulmonary Surfactant Deficiency

General Causes
Acidosis Hypoxia Hyperoxia Atelectasis Pulmonary vascular congestion
Specific Causes
Acute respiratory distress syndrome (ARDS) Respiratory distress syndrome (RDS) Pulmonary edema Pulmonary embolism Pneumonia Excessive pulmonary lavage or hydration Near drowning Extracorporeal oxygenation

In the healthy lung, both the elastic tension and the degree of surface tension are low in the small alveoli. As the alveoli increase in size, both the elastic tension and the degree of surface tension progressively increase. The elastic tension, however, is the predominant force, particularly in the large alveoli (Figure 2–38).

In the absence of pulmonary surfactant, the alveolar fluid lining behaves according to Laplace's law—that is, a high pleural pressure must be generated to keep the small alveoli open. When such a condition exists, the surface tension force predominates in the small alveoli (see Figure 2–38).

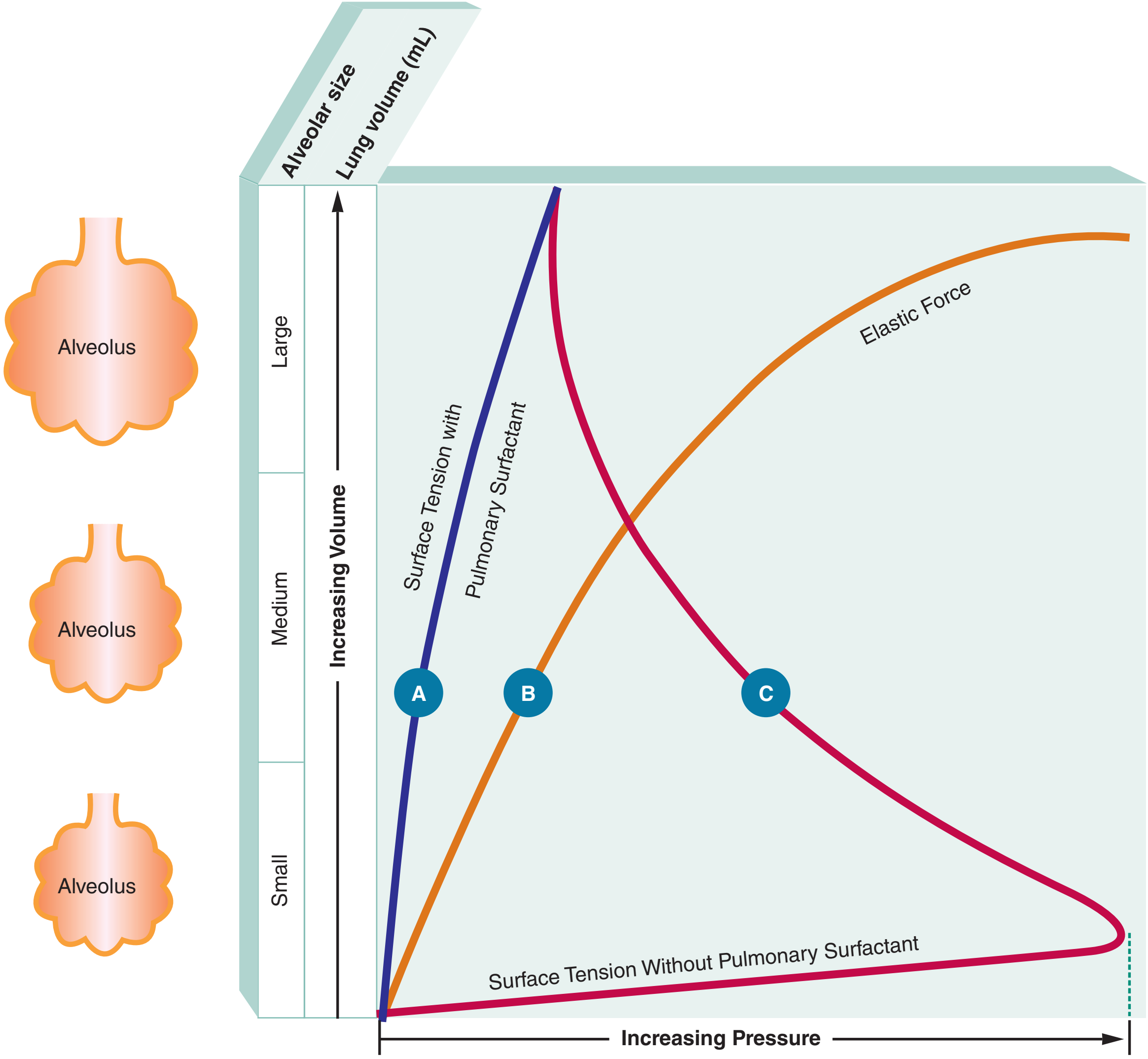
Clinical Connection 2-9

Pulmonary Surfactant Deficiency

The respiratory therapist will encounter a number of pulmonary disorders that are associated with a pulmonary surfactant deficiency. For example, this problem is commonly seen in premature infants who are diagnosed with **respiratory distress syndrome (RDS)**. These babies are born before their type II alveolar cells are mature enough to produce a sufficient amount of pulmonary surfactant. Low levels of pulmonary surfactant increase the surface tension forces in the lungs and, in severe cases, cause the alveoli to collapse (atelectasis). Alveolar collapse shifts the baby's pressure-volume curve to the right, decreases lung compliance, decreases the baby's oxygenation level, and increases the work of breathing.

The treatment of choice during the early stages of RDS is **continuous positive airway pressure (CPAP)**. CPAP works to (1) re-inflate the lungs, (2) decrease the work of breathing, and (3) return the baby's oxygenation level to normal. Mechanical ventilation, in these cases, is avoided as long as possible. Because of the pulmonary surfactant deficiency associated with RDS, the administration of exogenous surfactant preparations such as Curosurf® (poractant alfa) is often helpful.

FIGURE 2-38 In the normal lung, both the surface tension force (A) and the elastic force (B) progressively increase as the alveolus enlarges. The elastic force is the predominant force in both the small and the large alveoli. In the absence of pulmonary surfactant, the surface tension force (C) predominates in the small alveoli. The elastic force (B) still predominates in the large alveoli. Note that, as the alveolus enlarges, the pressure required to offset the "abnormal" surface tension force (C) ultimately decreases to the same pressure required to offset the "normal" surface tension force (B). Thus, it can be seen that when there is a deficiency of pulmonary surfactant, the surface tension of the small alveoli creates a high recoil force. If a high pressure is not generated to offset this surface tension force, the alveoli will collapse.



Dynamic Characteristics of the Lungs

The term **dynamic** refers to the study of forces in action. In the lungs, dynamic refers to the movement of gas in and out of the lungs and the pressure changes required to move the gas. The dynamic features of the lung are best explained by Poiseuille's law for flow and pressure and the airway resistance equation.

Poiseuille's (Pwah-Sōy) Law for Flow and Pressure Applied to the Bronchial Airways

During a normal inspiration, pleural pressure decreases from its normal resting level (about -3 to -6 cm H_2O pressure), which causes the bronchial airways to lengthen and to increase in diameter (*passive dilation*). During expiration, pleural pressure increases (or returns to its normal resting state), which causes the bronchial airways to decrease in length and in diameter (*passive constriction*) (Figure 2–39). Under normal circumstances, these anatomic changes of the bronchial airways are not remarkable. In certain respiratory disorders (e.g., emphysema, chronic bronchitis), however, bronchial gas flow and pleural pressure may change significantly, particularly during expiration, when passive constriction of the tracheobronchial tree occurs. The reason for this is best explained in the relationship of factors described in Poiseuille's law. Poiseuille's law can be arranged for either flow or pressure.

Poiseuille's Law Arranged for Flow

When Poiseuille's law is arranged for flow, it is written as follows:

$$\dot{V} = \frac{\Delta P r^4 \pi}{8 l \eta}$$

where η = the viscosity of a gas (or fluid), ΔP = the change of pressure from one end of the tube to the other, r = the radius of the tube, l = the length of the tube, $\dot{V}$ = the gas (or fluid) flowing through the tube, and π and 8 = constants, which will be excluded from the discussion.

The equation states that flow is directly proportional to P and r^4 and inversely proportional to l and η. In other words, flow will decrease in response to decreased P and tube radius, and flow will increase in response to decreased tube length and fluid viscosity. Conversely, flow will increase in response to an increased P and tube radius and decrease in response to an increased tube length and fluid viscosity.

It should be emphasized that flow is profoundly affected by the radius of the tube. As Poiseuille's law illustrates, $\dot{V}$ is a function of the fourth power of the radius (r^4). In other words, assuming that pressure (P) remains constant, decreasing the radius of a tube by one-half reduces the gas flow to $\frac{1}{16}$ of its original flow.

FIGURE 2-39 During inspiration, the bronchial airways lengthen and increase in diameter. During expiration, the bronchial airways decrease in length and diameter.

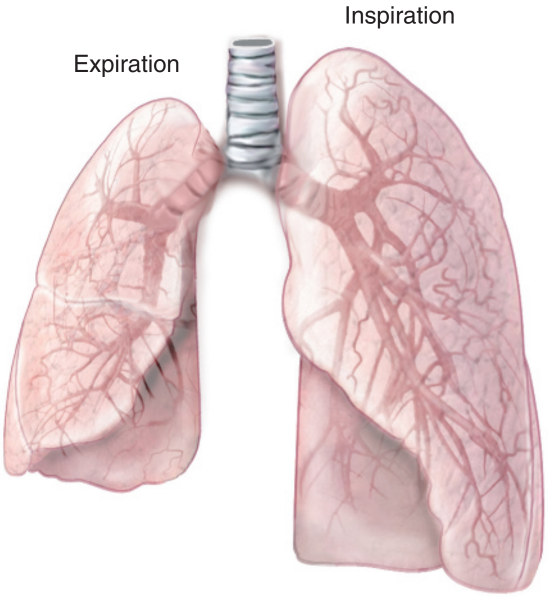
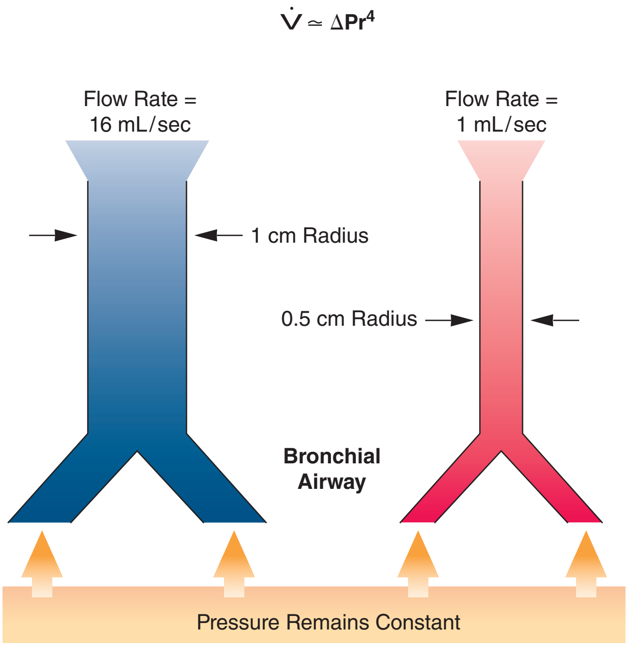


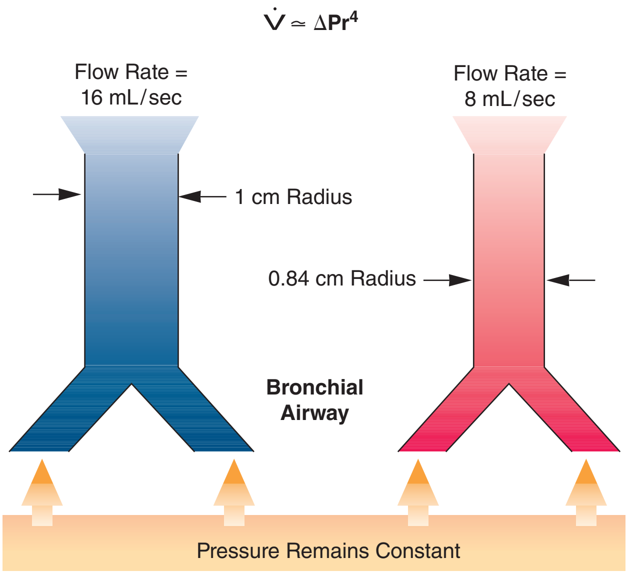
FIGURE 2-40 Poiseuille's law for flow applied to a bronchial airway with its radius reduced 50 percent.


$\dot{V} \simeq \Delta Pr^4$
Flow Rate = 16 mL/sec
Flow Rate = 1 mL/sec
1 cm Radius
0.5 cm Radius
Bronchial Airway
Pressure Remains Constant

For example, if the radius of a bronchial tube through which gas flows at a rate of 16 milliliters per second (mL/sec) is reduced to one-half of its original size because of mucosal swelling, the flow rate through the bronchial tube would decrease to 1 mL/sec (1⁄16 the original flow rate) (Figure 2–40).

Similarly, decreasing a tube radius by 16 percent decreases gas flow to one-half its original rate. For instance, if the radius of a bronchial tube through which gas flows at a rate of 16 mL/sec is decreased by 16 percent (e.g., because of mucosal swelling), the flow rate through the bronchial tube would decrease to 8 mL/sec (one-half the original flow rate) (Figure 2–41).

FIGURE 2-41 Poiseuille's law for flow applied to a bronchial airway with its radius reduced 16 percent.


$\dot{V} \simeq \Delta Pr^4$
Flow Rate = 16 mL/sec
Flow Rate = 8 mL/sec
1 cm Radius
0.84 cm Radius
Bronchial Airway
Pressure Remains Constant

Poiseuille's Law Arranged for Pressure

When Poiseuille's law is arranged for pressure, it is written as follows:

$$P = \frac{\dot{V}8l\eta}{r^4\pi}$$

The equation now states that pressure is directly proportional to $\dot{V}$, l, and η and inversely proportional to r^4. In other words, pressure will increase in response to a decreased tube radius and decrease in response to a decreased flow rate, tube length, or viscosity. The opposite is also true: pressure will decrease in response to an increased tube radius and increase in response to an increased flow rate, tube length, or viscosity.

Pressure is a function of the radius to the fourth power (r^4) and therefore is profoundly affected by the radius of a tube. In other words, if flow ($\dot{V}$) remains constant, then decreasing a tube radius to one-half of its previous size requires an increase in pressure to 16 times its original level.

If the radius of a bronchial tube with a driving pressure of 1 cm H_2O is reduced to one-half its original size because of mucosal swelling, the driving pressure through the bronchial tube would have to increase to 16 cm H_2O ($16 \times 1 = 16$) to maintain the same flow rate (Figure 2–42).

Similarly, decreasing the bronchial tube radius by 16 percent increases the pressure to twice its original level. For instance, if the radius of a bronchial tube with a driving pressure of 10 cm H_2O is decreased by 16 percent because of mucosal swelling, the driving pressure through the bronchial tube would have to increase to 20 cm H_2O (twice its original pressure) to maintain the same flow (Figure 2–43).

Poiseuille's Law Rearranged to Simple Proportionalities

When Poiseuille's law is applied to the tracheobronchial tree during spontaneous breathing, the two equations can be rewritten as simple proportionalities:

$$\dot{V} \approx Pr^4$$

$$P \approx \frac{\dot{V}}{r^4}$$

FIGURE 2-42 Poiseuille's law for pressure applied to a bronchial airway with its radius reduced 50 percent.

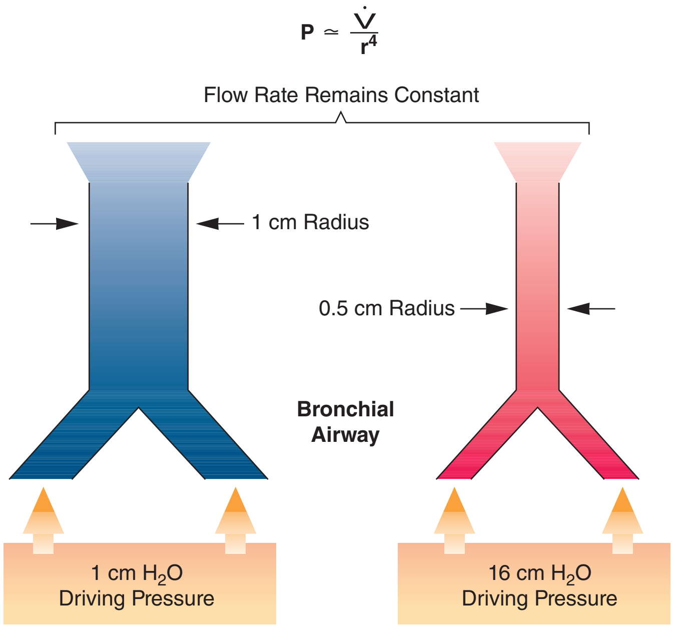
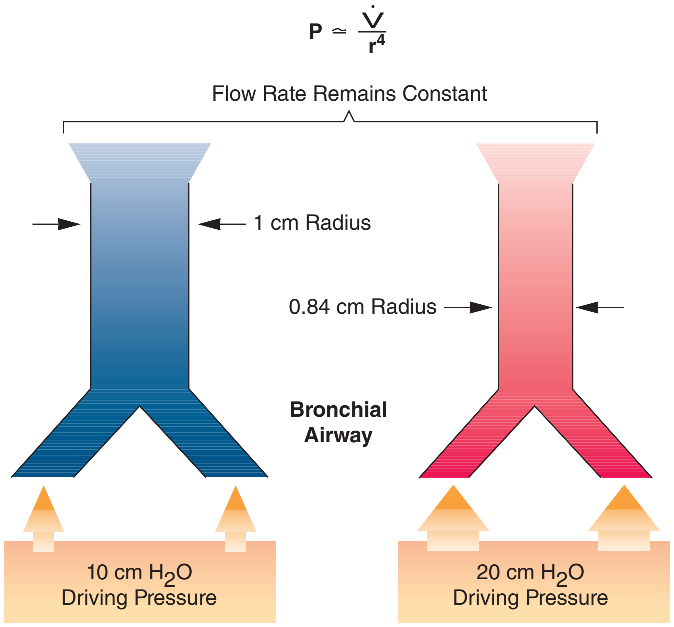

$P \simeq \frac{\dot{V}}{r^4}$
Flow Rate Remains Constant
1 cm Radius
0.5 cm Radius
Bronchial Airway
1 cm H_2O Driving Pressure
16 cm H_2O Driving Pressure

FIGURE 2-43 Poiseuille's law for pressure applied to a bronchial airway with its radius reduced 16 percent.


$P \simeq \frac{\dot{V}}{r^4}$
Flow Rate Remains Constant
1 cm Radius
0.84 cm Radius
Bronchial Airway
10 cm H_2O Driving Pressure
20 cm H_2O Driving Pressure

Based on the proportionality for flow, it can be stated that because gas flow varies directly with r^4 of the bronchial airway, flow must diminish during exhalation because the radius of the bronchial airways decreases. Stated differently, assuming that the pressure remains constant as the radius (r) of the bronchial

Clinical Connection 2-10

Respiratory Disorders That Decrease the Radius of the Airways

As described in more detail in the Clinical Application Case 2 (page 145), any obstructive respiratory disorder—such as asthma—that reduces the size of the bronchial airways can have a tremendous impact on gas flow and on the patient's work of breathing. Obstructive lung disorders include asthma (see Figure 2–23), chronic bronchitis (see Figure 2–49), cystic fibrosis (see Figure 1–28), and emphysema. Figure 2–44 provides an illustration of emphysema.

According to Poiseuille's law for **flow**, airflow is directly proportional to the radius of the airway—raised to the fourth power (r^4). This means that the flow of gas drastically decreases in response to only a small decrease in the radius of the bronchial airway. For example, if a patient, who normally generates an intrapleural pressure of –3 mm Hg to inhale 500 mL of air, suddenly experiences an acute asthmatic episode that reduces the radius of the bronchial airways by only 1⁄16 of their original size, the same negative intrapleural pressure change (−3 mm Hg) will only move 250 mL of gas during inspiration—in short, the patient's inspiration volume will be cut in half! To generate enough intrapleural pressure to inhale the original 500 mL, the patient will need to double the intrapleural pressure to −6 mm Hg—in short, double the work of breathing.

When applying Poiseuille's law for **pressure**, the intrapressure changes required to move gas are

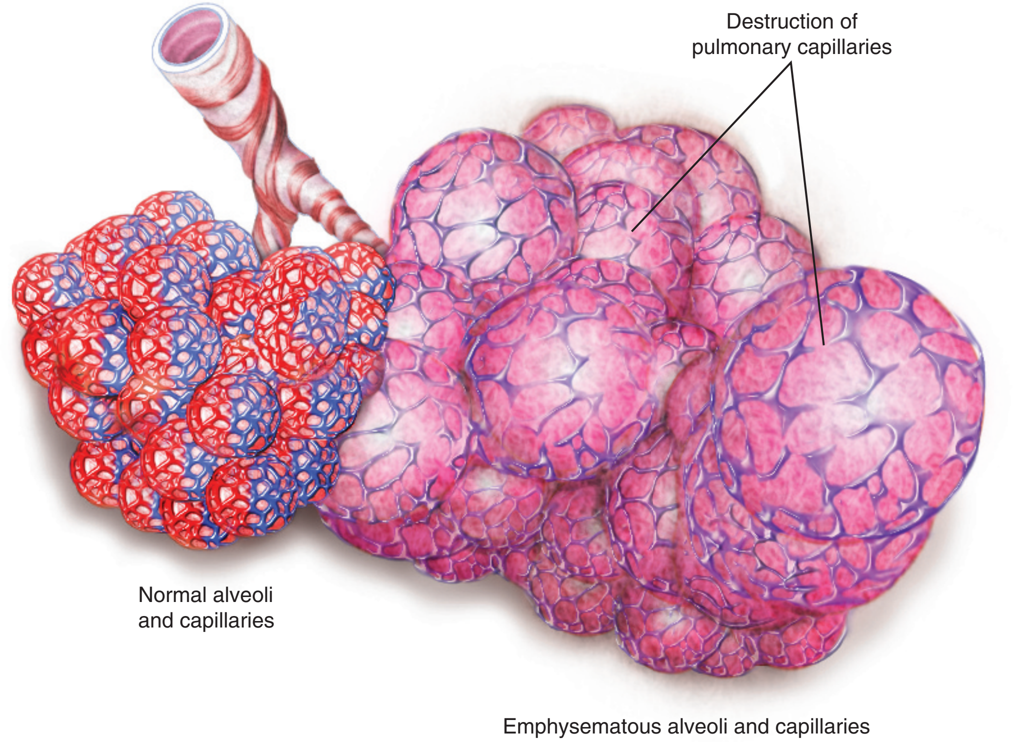
(Continued)

Clinical Connection 2-10, Continued

indirectly proportional to the radius of the airway—raised to the fourth power (r^4). Again, this means that the intrapleural pressure significantly increases in response to only a small decrease in the radius of the bronchial airway. For example, if a patient, who normally generates an intrapleural pressure of −3 mm Hg to inhale 500 mL of air, suddenly experiences an acute asthmatic episode that reduces the radius of the bronchial airways to one-half of their original size, the patient will need to generate a negative intrapleural pressure of −48 mm Hg to continue to inhale the same volume of gas (500 mL)—in short, the work of breathing will increase by a factor of 16 ($16 \times 3 = 48$).

See text for further discussion of Poiseuille's law.

FIGURE 2-44 Emphysema. Pathology includes (1) permanent enlargement and destruction of the alveoli distal to the terminal bronchioles; (2) destruction of the alveolar-capillary membrane; (3) weakening of the distal airways, primarily the respiratory bronchioles; and (4) air trapping and hyperinflation.


Destruction of pulmonary capillaries
Normal alveoli and capillaries
Emphysematous alveoli and capillaries

airways decreases, gas flow ($\dot{V}$) also decreases. During normal spontaneous breathing, however, the reduction in gas flow during exhalation is negligible.

In terms of the proportionality for pressure ($P \approx \dot{V} \div r^4$), if gas flow is to remain constant during exhalation, then the transthoracic pressure must vary inversely with the fourth power of the radius (r^4) of the airway. In other words, as the radius of the bronchial airways decreases during exhalation, the driving pressure must increase to maintain a constant gas flow.[5]

During normal spontaneous breathing, the need to increase the transrespiratory pressure during exhalation to maintain a certain gas flow is not significant. However, in certain respiratory disorders (e.g., emphysema, bronchitis, asthma), gas flow reductions and transthoracic pressure increases may be substantial as a result of the bronchial narrowing that develops in such disorders.

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[5] See mathematical discussion of Poiseuille's law in Appendix III.

Airway Resistance

Airway resistance (R_{aw}) is defined as the pressure difference between the mouth and the alveoli (*transrespiratory pressure*) divided by flow rate. In other words, the rate at which a certain volume of gas flows through the bronchial airways is a function of the pressure gradient and the resistance created by the airways to the flow of gas. Mathematically, R_{aw} is measured in centimeters of water per liter per second (L/sec), according to the following equation:

$$R_{aw} = \frac{\Delta P(\text{cm } H_2O)}{\dot{V}(\text{L/sec})}$$

For example, if an individual produces a flow rate of 4 L/sec during inspiration by generating a transrespiratory pressure of 4 cm H_2O, then R_{aw} would equal 1 cm H_2O/L/sec:

$$\begin{aligned} R_{aw} &= \frac{\Delta P}{\dot{V}} \\ &= \frac{4 \text{ cm } H_2O}{4 \text{ L/sec}} \\ &= 1 \text{ cm } H_2O/\text{L/sec} \end{aligned}$$

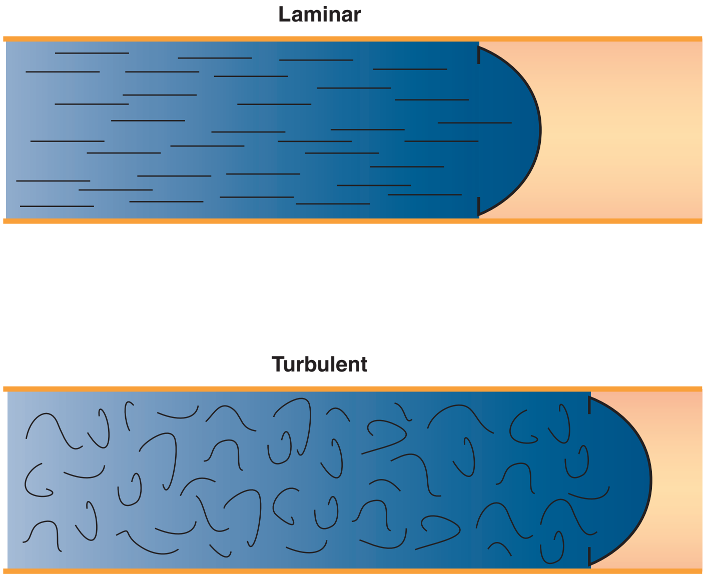
Normally, the R_{aw} in the tracheobronchial tree is about 0.5 to 1.5 cm H_2O/L/sec in adults. In patients with COPD (e.g., chronic bronchitis), however, R_{aw} may be high. The value of R_{aw} is also much higher in newborn infants than in normal adults (refer to Chapter 11).

The movement of gas through a tube (or bronchial airway) can be classified as (1) laminar flow, (2) turbulent flow, or (3) a combination of laminar flow and turbulent flow—called tracheobronchial flow or transitional flow (Figure 2–45).

Laminar Flow

Laminar gas flow refers to a gas flow that is streamlined. The gas molecules move through the tube in a pattern parallel to the sides of the tube. This flow pattern occurs at low flow rates and at low-pressure gradients.

FIGURE 2-45 Types of gas flow.



Turbulent Flow

Turbulent gas flow refers to gas molecules that move through a tube in a random manner. Gas flow encounters resistance from both sides of the tube and from the collision with other gas molecules. This flow pattern occurs at high flow rates and at high-pressure gradients.

Tracheobronchial or Transitional Flow

Tracheobronchial gas flow occurs in the areas where the airways branch. Depending on the anatomic structure of the branching airways and the velocity of gas flow, either laminar flow or turbulent flow may predominate.

Time Constants

A product of airway resistance (R_{aw}) and lung compliance (C_L) is a phenomenon called **time constant**, defined as the time (in seconds) necessary to inflate a particular lung region to about 60 percent[6] of its potential filling capacity. Lung regions that have either an increased R_{aw} or an increased C_L require more time to inflate. These alveoli are said to have a *long time constant*. In contrast, lung regions that have either a decreased R_{aw} or a decreased C_L require less time to inflate. These alveoli are said to have a *short time constant*.

Mathematically, the time constant (T_C) is expressed as follows:

$$T_c(\text{sec}) = \underset{(R_{aw})}{\frac{\Delta P(\text{cm } H_2O)}{\dot{V}(\text{L/sec})}} \times \underset{(C_L)}{\frac{\Delta V(\text{L})}{\Delta P(\text{cm } H_2O)}}$$

$$= \frac{\text{cm } H_2O \times \text{L}}{\text{L/sec} \times \text{cm } H_2O}$$

This equation shows that as R_{aw} increases, the value for pressure (P, in cm H_2O) in the numerator increases. Or, when C_L decreases, the value for volume (V) in liters (L) in the numerator decreases.

Thus, assuming that all other variables remain constant, if the R_{aw} of a specific lung region doubles, then the time constant will also double (i.e., the lung unit will take twice as long to inflate). In contrast, if the C_L is reduced by half, then the time constant will also be reduced by half—and, importantly, the potential filling capacity of the lung region is also reduced by half. To help illustrate this concept, consider the time constants illustrated in Figure 2–46.

In Figure 2–46A, two alveolar units have identical R_{aw} and C_L. Thus, the two alveoli require the same amount of time to inflate—they have the same time constants.

Figure 2–46B shows two alveolar units with the same R_{aw} but with two different C_L. Because the C_L in unit B is one-half the C_L of unit A, unit B (low compliance) receives one-half the volume of unit A (high compliance). It is important to realize that unit B has a shorter time constant than unit A and unit B receives only one-half the volume received by unit A.

In Figure 2–46C, the two alveolar units have the same compliance but two different R_{aw}. Because the R_{aw} leading to unit B is twice the R_{aw} leading to unit A, unit B (high R_{aw}) requires twice the time to fill to the same volume as unit A (low R_{aw}). It is important to note that the two alveolar units do not have the same time constant—the time constant for unit B is twice that of unit A. Thus, it is also important to note that as the breathing frequency increases, the time necessary to fill unit B may not be adequate. Clinically, how readily a lung region fills with gas during a specific time period is called **dynamic compliance**.

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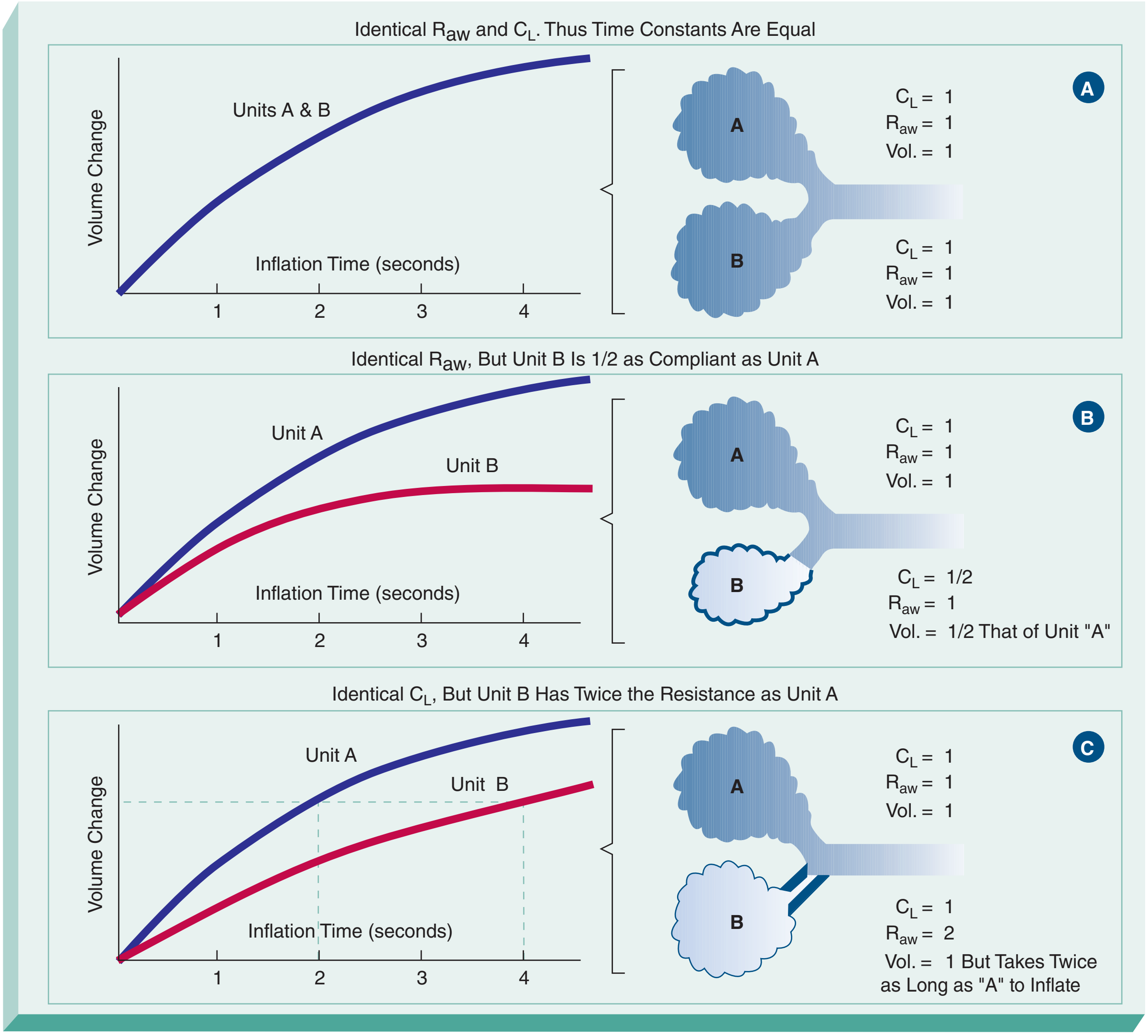
[6] Technically, 63 percent.

FIGURE 2-46 Time constants for hypothetical alveoli with differing lung compliances (C_L), supplied by airways with differing resistances (R_{aw}).



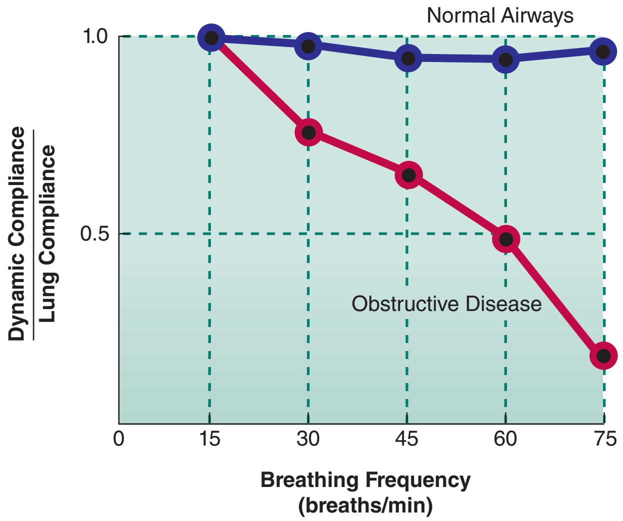
Dynamic Compliance

The measurement called dynamic compliance is a product of the time constants. Dynamic compliance is defined as the change in the volume of the lungs divided by the change in the transpulmonary pressure (obtained via a partially swallowed esophageal pressure balloon) during the time required for one breath. Dynamic compliance is distinctively different from the lung compliance (C_L) defined earlier in this chapter as the change in lung volume (ΔV) per unit pressure change (ΔP) (see Figure 2–21). In short, lung compliance is determined during a period of no gas flow, whereas dynamic compliance is measured during a period of gas flow.

In the healthy lung, the dynamic compliance is about equal to lung compliance at all breathing frequencies (the ratio of dynamic compliance to lung compliance is 1:1) (Figure 2–47).

In patients with partially obstructed airways, however, the ratio of dynamic compliance to lung compliance falls significantly as the breathing frequency rises (see Figure 2–47). In other words, the alveoli distal to the obstruction do not have enough time to fill to their potential filling capacity as the breathing frequency increases. The compliance of such alveoli is said to be **frequency dependent**.

FIGURE 2-47 Dynamic compliance/lung compliance ratio at different breathing frequencies. In normal individuals, there is essentially no ratio change. In individuals with obstructive disorders, however, the ratio decreases dramatically as the respiratory rate increases.



Clinical Connection 2-11

Endotracheal Size and Poiseuille's law

In addition to the importance of the proper placement of the endotracheal tube (see Clinical Connection 1–10), and potential tracheal cuff erosion hazards (see Clinical Connection 1–15), the respiratory therapist must always be mindful of diameter of the endotracheal tube (Figure 2–48). While care must always be taken to not insert too large of tube diameter that may cause laryngeal trauma, there are also potential pitfalls to selecting a tube size too small.

As shown by Poiseuille's law, even small changes in the radius of the endotracheal tube will have a profound effect on airway resistance—either in terms of pressure or flow. For example, according to Poiseuille's law, if instead of placing a 5.0 mm ID endotracheal tube an endotracheal tube only 1.0 mm smaller at 4.0 mm ID (a 20 percent reduction) is selected, the flow rate through the tube would (1) decrease by more than 60 percent or (2) the ventilatory pressure changes needed to maintain the original flow rate (i.e., through the 5.0 mm ID tube) would have to increase by over 60 percent.

In addition, consider this: If the patient is intubated and breathing via a mechanical ventilator that is in a **volume-controlled mode**, the increase in airway resistance will require an increase in the ventilating pressure as the machine delivers gas down a smaller diameter tube. In this case, an increase from 10 cm H_2O to 16 cm H_2O (an increase of over 60 percent). In contrast, if the patient is being ventilated via a mechanical ventilator in a **pressure-controlled mode**, the increased resistance will result in a potentially decreased tidal volume delivery—unless the ventilator is adjusted to deliver a higher inspiratory pressure. In this case, the pressure would have to be increased from 10 cm H_2O to 16 cm H_2O (an increase of over 60 percent). Finally, for a patient breathing spontaneously, the increased resistance will require an increase in the work of breathing as the patient generates the necessary pressure gradient changes needed to move gas through the endotracheal tube—a substantial increase in the work of breathing for the patient.

The correct sized endotracheal tube is critical for optimal patient care. The intubator should always

Clinical Connection 2-11, Continued

strive to use the largest diameter tube that will pass through the larynx without causing trauma to the soft tissue at its narrowest portion. Remember: the smallest part of the upper airway for the adult is the glottis. In the infant and child, the smallest portion of the upper airway is the cricoid cartilage. Therefore, the patient's anatomy will determine the maximum size that will pass through the smallest part of the larynx before it passes into the larger diameter of the trachea where its distal tip rests. Choosing the largest size that will pass through the larynx will help assure that an increase in airway resistance is minimized. Selecting the optimal size endotracheal tube for each patient is critical. Either too large or too small of a tube can have untoward effects.

FIGURE 2-48 Endotracheal tube sizes. The French gauge scale is 3 times the diameter in millimeters (mm). For example, a 9 French gauge tube has a 3 mm (9/3 = 3) outside diameter.

Size	I.D. (mm)	O.D. (mm)
Fr 8	2.0	3.0
Fr 10	2.5	3.3
Fr 12	3.0	4.0
Fr 14	3.5	4.7
Fr 16	4.0	5.3
Fr 18	4.5	6.0
Fr 20	5.0	6.7
Fr 22	5.5	7.3
Fr 24	6.0	8.0
Fr 26	6.5	8.7
Fr 28	7.0	9.3
Fr 30	7.5	10.0
Fr 32	8.0	11.3
Fr 34	8.5	12.0

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Clinical Connection 2-12

Restrictive Lung Disorders, Time Constants, and Breathing Pattern Relationships

Common restrictive respiratory disorders that decrease lung compliance (C_L)—and, therefore, decrease the time constant—include atelectasis, pneumonia, pneumothorax, pleural effusion, pulmonary edema, acute respiratory distress syndrome, and interstitial lung diseases. A decreased time constant simply means that the actual time it takes to inflate stiff—noncompliant—alveoli is shorter, but at the undesirable cost of less alveolar volume.

To offset the decreased C_L—and, therefore, the decreased lung volume—associated with these respiratory disorders, the patient typically adopts a faster ventilatory rate. In other words, because the patient is only able to inhale smaller tidal volumes, they simply breathe more times per minute. This breathing pattern works to maintain the overall minute volume at, or beyond, the patient's normal minute volume.

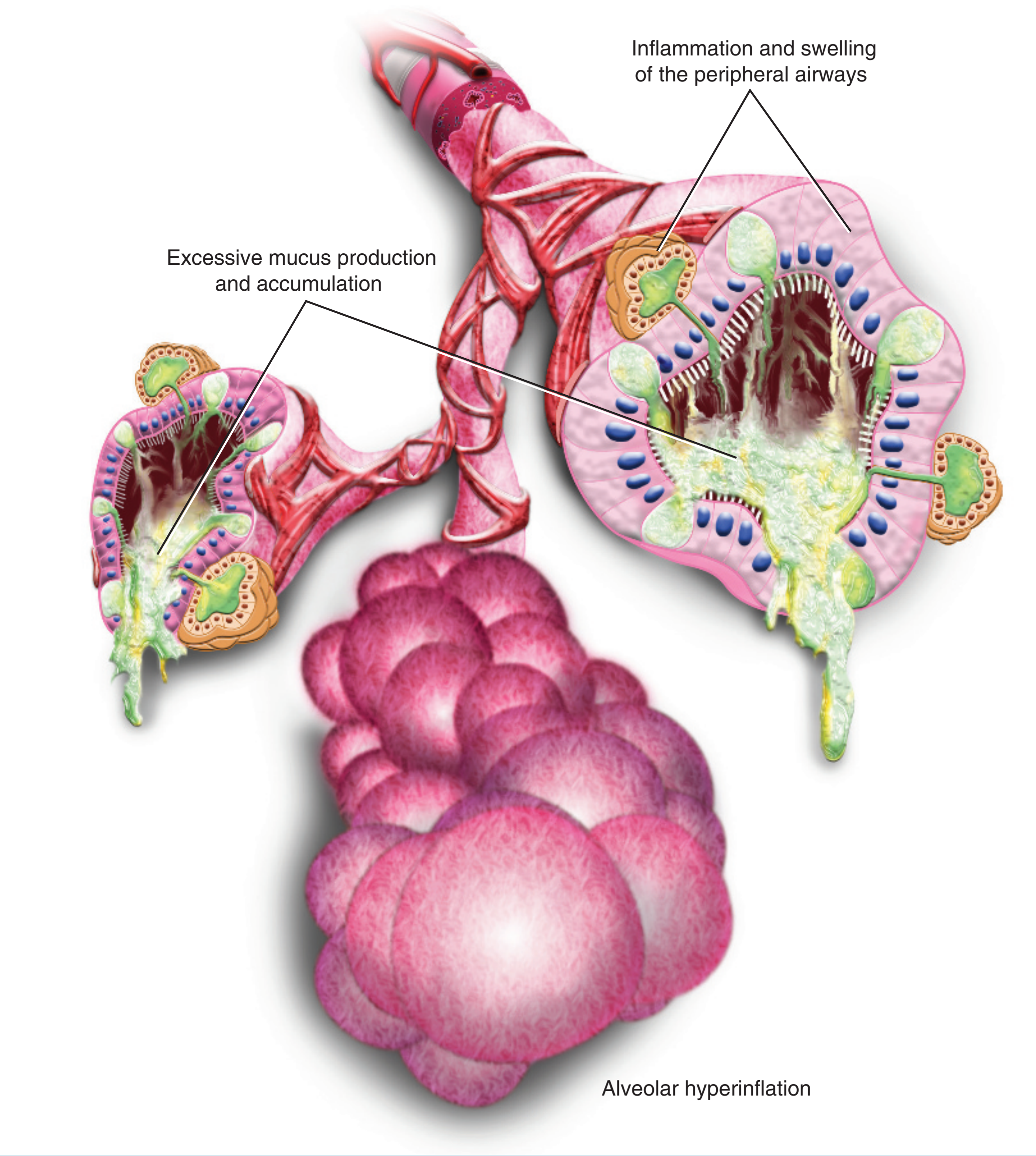
Clinical Connection 2-13

Obstructive Lung Disorders, Time Constants, and Breathing Pattern Relationships

Common obstructive respiratory disorders that increase airway resistance (R_{aw})—and, therefore, increase the time constant—include asthma, chronic bronchitis, emphysema, and cystic fibrosis.

Figure 2–49 shows the major bronchial airway changes associated with chronic bronchitis. A longer time constant simply means that the actual time it takes to inflate the alveoli is longer. This is because

FIGURE 2-49 Chronic bronchitis. Pathology includes (1) inflammation and swelling of the peripheral airways, (2) excessive mucus production and accumulation, and (3) alveolar hyperinflation. Because of the abnormal airway changes associated with chronic bronchitis, there is an increased resistance (R_{aw}) and an increased time constant. The patient's lung compliance is said to be **frequency dependent**—the faster the ventilator rate, the smaller the volume of air moved.


Inflammation and swelling of the peripheral airways
Excessive mucus production and accumulation
Alveolar hyperinflation

Clinical Connection 2-13, Continued

it takes more time for gas to move through partially obstructed (↑R_{aw}) bronchial airways—similar to trying to inhale normally through a straw.

An interesting irony in these cases is that the faster the patient's ventilatory rate, the smaller the volume of air they inhale during each breath—the patient's lung compliance (C_L) is then said to be **frequency dependent**.

To offset the increased R_{aw}—and, therefore, the decreased lung volume—associated with obstructive respiratory disorders, the patient typically adopts a slower ventilatory rate and a larger tidal volume per breath. By slowing the ventilatory rate down and taking deeper breaths, the overall minute volume will remain at, or near, the patient's normal.

Clinical Connection 2-14

Auto-PEEP and Its Relationship to Airway Resistance during Rapid Ventilatory Rates

During rapid ventilatory rates, small airways with high R_{aw} may not have sufficient time to fully deflate during exhalation. The pressure in the alveoli distal to these airways may still be positive (greater than the atmospheric pressure) when the next inspiration begins. Clinically, the **positive end-expiratory pressure (PEEP)** caused by inadequate expiratory time is called **auto-PEEP**.[7] Auto-PEEP increases a patient's *work of breathing* (WOB) in two ways:

1. As a result of auto-PEEP, the patient's *functional residual capacity* (FRC) increases (refer to Chapter 3). When the FRC increases, the patient is forced to breathe at a higher, less compliant, point on the *pressure-volume curve* (see Figure 2–21). Thus, air trapping and alveolar hyperinflation (auto-PEEP) decrease lung compliance, causing the WOB to increase.
2. When auto-PEEP produces air trapping and alveolar hyperinflation, the patient's diaphragm is pushed downward; this causes the patient's inspiratory efforts to become less efficient, causing the WOB to increase. Normally, an individual needs to create an inspiratory effort that causes the alveolar pressure (P_A) to decrease -1 or 2 cm H_2O below the ambient pressure to cause air to flow into the alveoli. When auto-PEEP is present, the P_A is higher than the ambient pressure at the beginning of inspiration. For example, if as a result of auto-PEEP the P_A is $+4$ cm H_2O (above atmospheric pressure), then the inspiratory effort must decrease the P_A more than 4 cm H_2O before gas can start to flow into the lungs, requiring an increased WOB.

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[7] Auto-PEEP is also called *air trapping*, *intrinsic PEEP*, *occult PEEP*, *inadvertent PEEP*, and *covert PEEP*.

Ventilatory Patterns

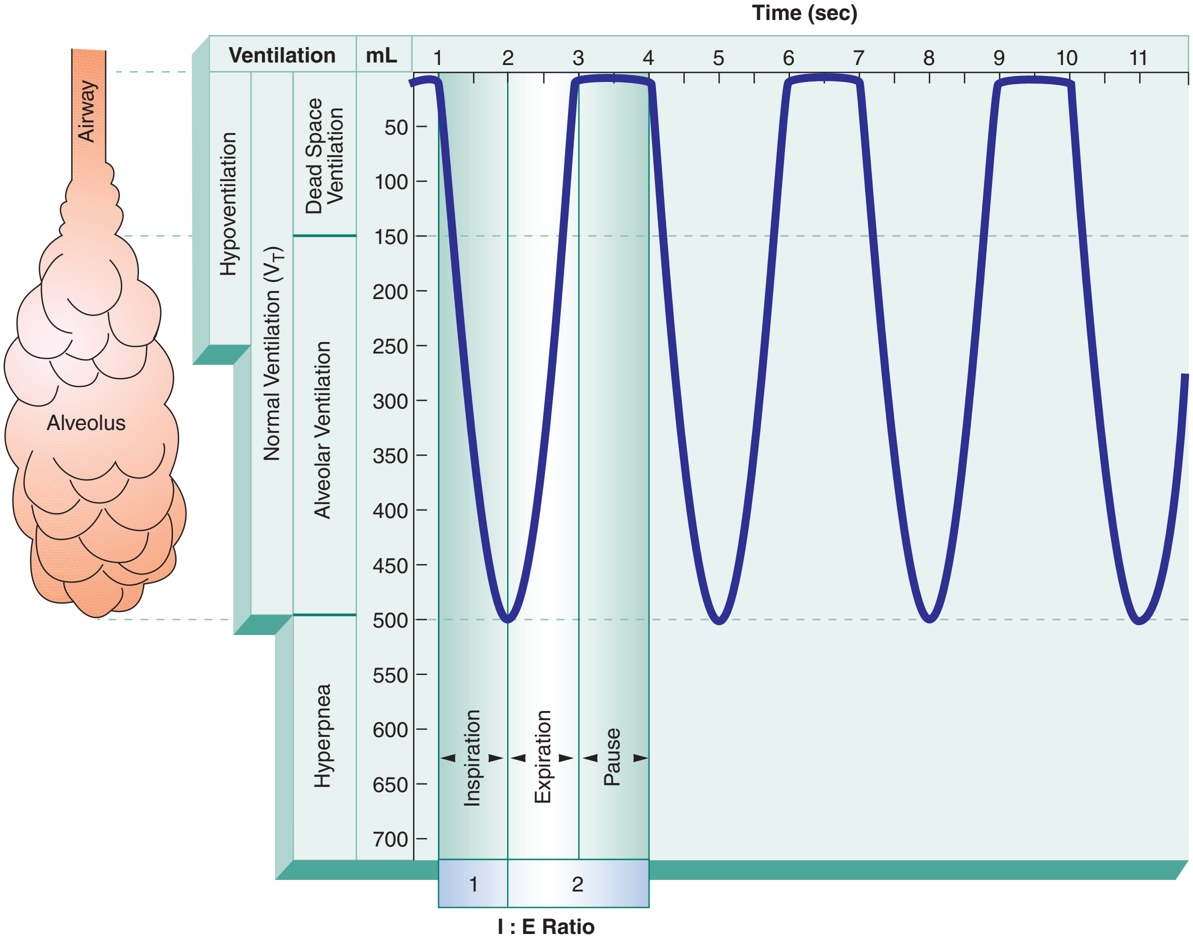
The Normal Ventilatory Pattern

The ventilatory pattern consists of (1) the tidal volume (V_T), (2) the ventilatory rate, and (3) the time relationship between inhalation and exhalation (I:E ratio).

Tidal volume is defined as the volume of air that normally moves into and out of the lungs in one quiet breath. Normally, the V_T is about 5 to 7 mL/kg (3 to 4 mL/lb) of ideal body weight (IBW). The average V_T is about 500 mL. The normal adult ventilatory rate is 12 to 18 breaths per minute (bpm) (average 15 bpm). The I:E ratio is usually about 1:2. That is, the time required to inhale a normal breath is about one-half the time required to exhale the same breath.

Technically, however, the time required to inhale and exhale while at rest is about equal (a 1:1 ratio) in terms of "true" gas flow. The reason exhalation is considered twice as long as inhalation in the I:E ratio

FIGURE 2–50 Normal, spontaneous breathing (eupnea). The I:E ratio typically is 1:2.



is that the ratio includes the normal pause, during which there is no gas flow, that typically occurs at end-expiration as part of the exhalation phase (Figure 2–50).

This normal pause that occurs at end-exhalation is usually about equal, in terms of time, to either the inspiratory or expiratory phase. Thus, when an individual is at rest, the time required for a normal ventilatory cycle consists of approximately three equal phases: (1) the inspiratory phase, (2) the expiratory phase, and (3) the pause phase at end-expiration (see Figure 2–50).

Clinical Connection 2-15

Normal Respiratory Rates for Different Age Groups

In the clinical setting, there are wide ranges of patient ages that are receiving respiratory care. Because the normal breathing rate varies between the different age groups, the respiratory therapist must have working knowledge of what is a normal respiratory rate among the different age groups—even when the rate is very fast (e.g., newborn infants and toddlers). The average, normal breathing rate range according to different age groups is as follows:

Clinical Connection 2-15, Continued

Normal Respiratory Rates for Different Age Groups

Age Group	Age	Breathing Rate
Newborn infant	1 month–1 year	30–60
Toddler	1–3 years	25–40
Preschooler	3–6 years	20–35
Child	6–12 years	20–30
Adolescent	12–18 years	12–20
Adult	19+ years	12–20

The reader is challenged to quietly observe the breathing rates of people in different age groups.

Clinical Connection 2-16

Tidal Volume and Breathing Rate Strategies for Mechanical Ventilation

Although the precise tidal volume and breathing rate selected for a patient on a mechanical ventilator is always based on the patient's specific needs—for example, patient history, arterial blood gas values, chest X-rays, and cardiac status—a generally accepted starting point for some specific pulmonary disorders are as follows:

Common Assist-Control Mechanical Ventilatory Management Strategies Good Starting Points

Pulmonary Status	Disease Characteristic	Tidal Volume	Ventilatory Set Rate—Breaths per Minute (bpm)
Normal lung mechanics	Normal compliance and airway resistance	4–8 mL/kg of IBW	10–12 bpm
Asthma, bronchitis, or emphysema (COPD)	High airway resistance, high lung compliance with COPD	4–8 mL/kg When air-trapping is extensive, a lower V_T (5–6 mL/kg) may be helpful.	10–12 bpm When air-trapping is extensive, a slower rate may be required.
Acute respiratory distress syndrome	Low lung compliance due to diffuse, uneven alveolar injury	8 mL/kg, adjusted downward to 6 mL/kg	As high as 35 bpm
Postoperative ventilatory support (e.g., coronary artery bypass surgery)	Often normal compliance and airway resistance	4–8 mL/kg	12 bpm
Neuromuscular disorder (e.g., myasthenia gravis or Guillain-Barré syndrome)	Normal compliance and airway resistance	4–8 mL/kg	10–12 bpm

Alveolar Ventilation versus Dead Space Ventilation

Only the inspired air that reaches the alveoli is effective in terms of gas exchange. This portion of the inspired gas is referred to as **alveolar ventilation**. The volume of inspired air that does not reach the alveoli is not effective. This portion of gas is referred to as **dead space ventilation** (Figure 2–51). There are three types of dead space: (1) **anatomic**, (2) **alveolar**, and (3) **physiologic**.

Anatomic Dead Space

Anatomic dead space is the volume of gas in the conducting airways: the nose, mouth, pharynx, larynx, and lower airways down to, but not including, the respiratory bronchioles. The volume of anatomic dead space is approximately equal to 1 mL/lb (2.2 mL/kg) of "ideal" body weight. Thus, if an individual weighs 150 pounds, approximately 150 mL of inspired gas would be anatomic dead space gas (or physiologically ineffective).

Moreover, because of the anatomic dead space, the gas that does enter the alveoli during each inspiration (alveolar ventilation) is actually a combination of anatomic dead space gas (non-fresh gas) and gas from the atmosphere (fresh gas). To visualize this, consider the inspiration and expiration of 450 mL (V_T) in an individual with an anatomic dead space of 150 mL (Figure 2–52).

Inspiration. As shown in Figure 2–52A, 150 mL of gas fill the anatomic dead space at pre-inspiration. This gas was the last 150 mL of gas to leave the alveoli during the previous exhalation. Thus, as shown in Figure 2–52B, the first 150 mL of gas to enter the alveoli during inspiration are from the anatomic dead space (non-fresh gas). The next 300 mL of gas to enter the alveoli are from the atmosphere (fresh gas). The last 150 mL of fresh gas inhaled fill the anatomic dead space (see Figure 2–52B). Thus, of the 450 mL of gas that enter the alveoli, 150 mL come from the conducting airways (non-fresh gas) and 300 mL come from the atmosphere (fresh gas).

FIGURE 2-51 Dead space ventilation (V_D).

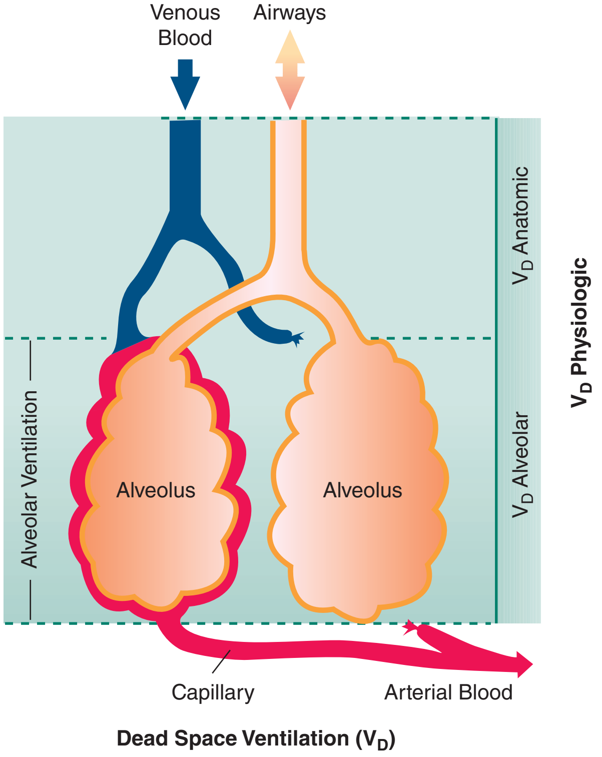
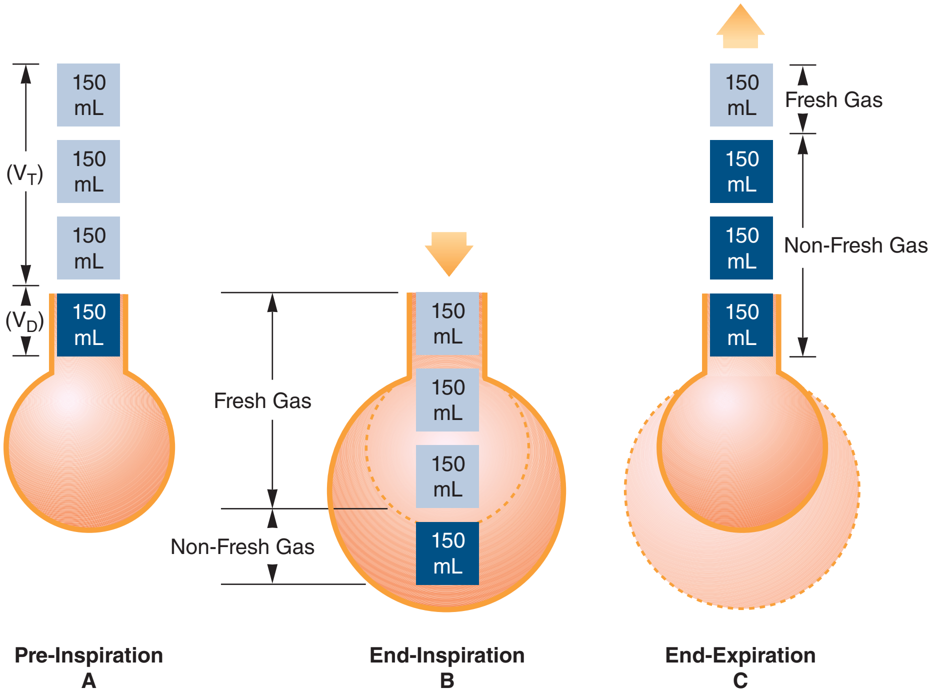


FIGURE 2-52 Alveolar ventilation versus dead space ventilation during one ventilatory cycle.


150 mL
150 mL
150 mL
150 mL
(V_T)
(V_D)
Fresh Gas
Non-Fresh Gas
150 mL
150 mL
150 mL
150 mL
Fresh Gas
Non-Fresh Gas
150 mL
150 mL
150 mL
150 mL
Pre-Inspiration
A
End-Inspiration
B
End-Expiration
C

Expiration. As shown in Figure 2–52C, 450 mL of gas are forced out of the alveoli during expiration. The first 150 mL of gas exhaled are from the anatomic dead space. This gas was the last 150 mL that entered the conducting airways during the previous inspiration (see Figure 2–52B). The next 300 mL of gas exhaled come from the alveoli. The last 150 mL of gas to leave the alveoli fill the anatomic dead space. During the next inspiration, the last 150 mL of gas exhaled from the alveoli will, again, reenter the alveoli, thus diluting the oxygen concentration of any atmospheric gas that enters the alveoli (see Figure 2–52A).

Therefore, minute alveolar ventilation (V_A) is equal to the tidal volume (V_T) minus the dead space ventilation (V_D) multiplied by the breaths per minute (frequency):

$$\dot{V}_A = (V_T - V_D) \times \text{breaths/min}$$

For example, if:

$$V_T = 450 \text{ mL}$$

$$V_D = 150 \text{ mL}$$

breaths/min = 12
then minute alveolar ventilation would be computed as follows:

$$\begin{aligned}\dot{V}_A &= V_T - V_D \times \text{breaths/min}\\ &= 450 \text{ mL} - 150 \text{ mL} \times 12\\ &= 300 \text{ mL} \times 12\\ &= 3600 \text{ mL}\end{aligned}$$

Finally, an individual's breathing pattern (depth and rate of breathing) can profoundly alter the total alveolar ventilation. For example, Table 2–2 shows three different subjects, each having a total minute ventilation (MV) of 6000 mL and each having an anatomic dead space volume of 150 mL. Each subject, however, has a different tidal volume and breathing frequency. Subject A has a tidal volume of 150 mL and a

TABLE 2-2 Effect of Breathing Depth and Frequency on Alveolar Ventilation

Subject	Breathing Depth (V_T) (mL)		Breathing Frequency (breaths/min)		Total MV* (mL/min)	V_D† (mL/min)	V_A‡ (mL/min)
A	150	×	40	=	6000	150 × 40 = 6000	0
B	500	×	12	=	6000	150 × 12 = 1800	4200
C	1000	×	6	=	6000	150 × 6 = 900	5100

* Total alveolar ventilation, or minute ventilation (MV), is the product of breathing depth, or tidal volume (V_T), times breathing frequency, or breaths per minute.

† Total dead space ventilation (V_D) is the product of anatomic dead space volume (150 mL in each subject) times breathing frequency.

‡ V_A = alveolar ventilation.

breathing frequency of 40 breaths/min. Even though gas rapidly moves in and out of the lungs, the actual alveolar ventilation is zero. Subject A is merely moving 150 mL of gas in and out of the anatomic dead space at a rate of 40 times per minute. Clinically, this subject would become unconscious in a few minutes.

Subject B has a tidal volume of 500 mL and a breathing frequency of 12 breaths/min. This subject has an alveolar ventilation of 4200 mL. Subject C has a tidal volume of 1000 mL and a frequency of 6 breaths/min. This subject has an alveolar ventilation of 5100 mL.

The important deduction to be drawn from Table 2–2 is this: **an increased depth of breathing is far more effective than an equivalent increase in breathing rate in terms of increasing an individual's total alveolar ventilation**. Or, conversely, a decreased depth of breathing (decreased tidal volume) can lead to a significant and, perhaps, a critical reduction of alveolar ventilation. This is because the anatomic dead space volume represents a fixed volume (normally about one-third), and the fixed volume will make up a larger portion of a decreasing tidal volume. This fraction increases as the tidal volume decreases until, as demonstrated by subject A, it represents the entire tidal volume. On the other hand, any increase in the tidal volume beyond the anatomic dead space goes entirely toward increasing alveolar ventilation.

Alveolar Dead Space

Alveolar dead space occurs when an alveolus is ventilated but not perfused with pulmonary blood. Thus, the air that enters the alveolus is not effective in terms of gas exchange, because there is no pulmonary capillary blood flow. The amount of alveolar dead space is unpredictable.

Clinical Connection 2-17

The Dead Space Ventilation Associated with Snorkeling

Dead space ventilation is defined as gas that does not undergo complete gas exchange. Examples include *anatomic dead space* (the conducting airways), *alveolar dead space* (un perfused alveoli), and deadspace effect (underperfused alveoli). *Physiologic dead space* is the sum of anatomic dead space, alveolar dead space, and deadspace effect (see Figure 2–51). Another type of dead space ventilation is **mechanical dead space**, which is defined as the volume of gas inhaled and exhaled through an additional length of tubing exterior to the body. Mechanical dead space can be found in ventilator circuits and consists of the tubing between the patient's artificial airway and the tubing wye. The volume of gas in this tubing is rebreathed—breath by breath—and forms a type of wasted ventilation or rebreathing of exhaled gases.

Like the dead space ventilation illustrated in Figure 2–52, the mechanical dead space in a snorkel is

Clinical Connection 2-17, Continued

yet an additional volume of gas that must be inhaled and exhaled during each breathing cycle (Figure 2–53). Like the normal anatomic dead space, the last portion of gas exhaled (non-fresh gas) remains in both the snorkel tube and conducting airways. Thus, during each inspiration the first volume of gas that enters the alveoli is non-fresh gas from both the conducting airways and the snorkel tube. In essence, the snorkel tube is an extension of an individual's normal *anatomic dead space*. It should be understood that to have an adequate alveolar ventilation, the snorkeler must compensate—that is, in terms of the depth of each inspiration and exhalation—to offset the volume needed to fill both their normal anatomic dead space and the snorkel tube.

The reader is challenged to think about the possible limits of a snorkel's size. In other words, at what diameter, or length, does the size of the snorkel prevent adequate alveolar ventilation? In addition, consider a normal inspiration and what volume of gas is (1) needed to fill both the conducting airways and the snorkel tube and (2) what volume of gas is still available for alveolar ventilation?

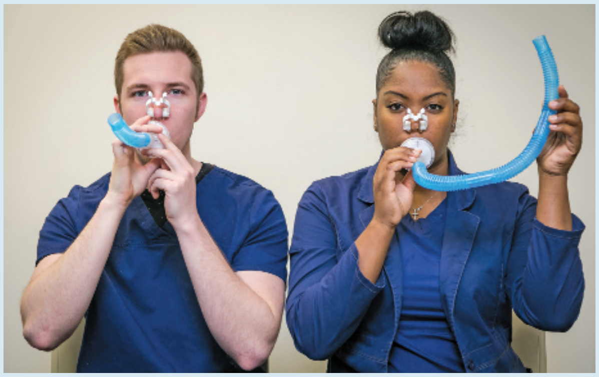
Is the diameter of the snorkel significant, that is, additional volume of gas occupying space? How long can a snorkel be and still allow adequate alveolar ventilation? Does this then limit to what depth the snorkeler can descend and still have access to atmospheric air for ventilation?

In the lab setting, the reader is again challenged to breathe through increasingly longer lengths of large bore corrugated tubing (each section is about 50 mL) (Figure 2–54). What is the length of the corrugated tubing when breathing becomes uncomfortable? What is the volume of the large bore tubing at the point at which breathing becomes too uncomfortable?

FIGURE 2-53 Snorkel breathing.

© BlueOrange Studio/Shutterstock.com.

FIGURE 2-54 Respiratory therapy students breathing through different lengths of large bore tubing in the lab setting to experience the sensation of dead space ventilation.



Courtesy of Gayle Carr

Clinical Connection 2-18

A Giraffe's Neck: Alveolar Ventilation versus Dead Space Ventilation

It is interesting to note that a giraffe's neck (anatomic dead space) can be up to 12 feet long (Figure 2–55). Although the giraffe's trachea has a small diameter relative to the length, it is estimated that the trachea dead space ventilation is about 3 L of gas per breath. Fortunately, the giraffe's lungs are capable of accommodating between 4 and 15 L of air per breath. This large volume of gas is more than enough to offset the 3 L of dead space ventilation. The giraffe's normal respiratory rate is about ⅓ of a human—or about 6 breaths per minute.

The reader is challenged to cut a yard of large bore corrugated tubing, and then attempt to breathe in and out through the tube as long as possible—similar to breathing through a snorkel. How long do you think you can breathe through the tubing before you feel very short of breath? How much more air would you need to inhale to move fresh gas into your lungs? Consider how the tubing—between the tubing circuitry on a mechanical ventilator and the endotracheal tube—might affect the patient's dead space ventilation.

FIGURE 2-55 A giraffe's anatomic dead space is about 3 L.

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Clinical Connection 2-19

Pulmonary Embolus and Dead Space Ventilation

A blood clot that travels through the venous system and lodges in the pulmonary arteries or arterioles is called a **pulmonary embolus**. A pulmonary embolus reduces or completely blocks the pulmonary blood flow from traveling farther downstream to the alveoli. As a result, the alveolar ventilation beyond the obstruction is wasted, or dead space, ventilation. In other words, no carbon dioxide or oxygen exchanges can occur in these alveoli. Pulmonary embolisms are extremely dangerous. The respiratory therapist should always be on alert for this respiratory disorder—particularly in patients with a recent history of bone fractures (especially the pelvis and long bones of the lower extremities), prolonged inactivity, hypercoagulation disorders, pregnancy and childbirth, and obesity.

Physiologic Dead Space

Physiologic dead space is the sum of the anatomic dead space and alveolar dead space. Because neither of these two forms of dead space is effective in terms of gas exchange, the two forms are combined and are referred to as physiologic dead space.

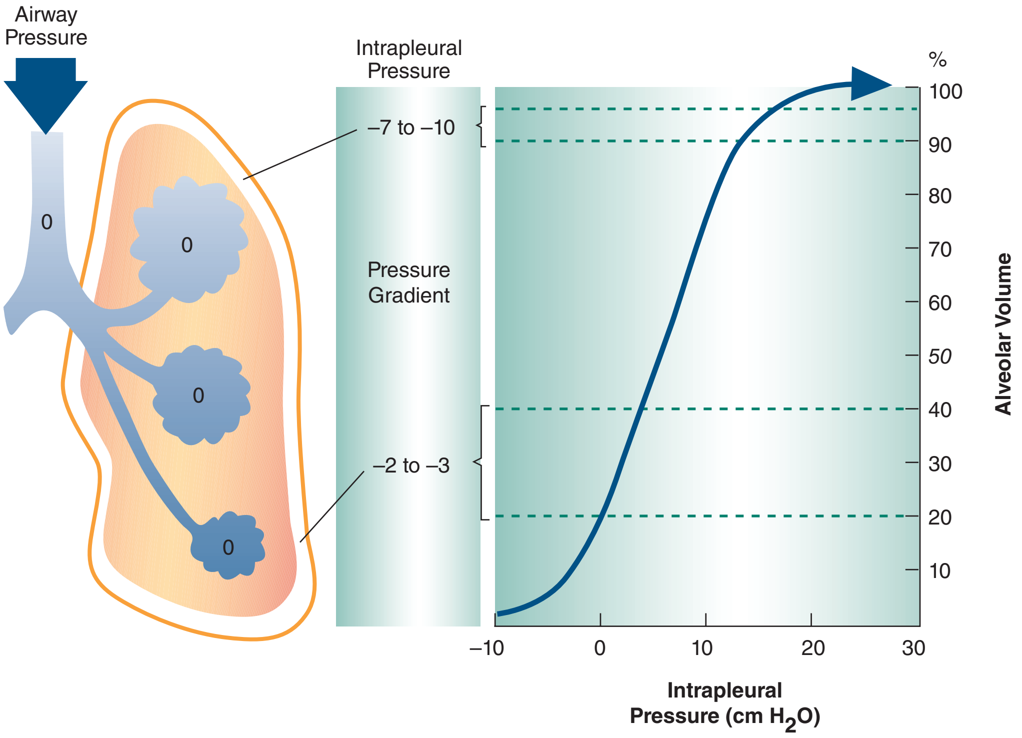
How Normal Pleural Pressure Differences Cause Regional Differences in Normal Lung Ventilation

As discussed earlier, the diaphragm moves air in and out of the lungs by changing the pleural and intra-alveolar pressures. Ordinarily, the pleural pressure is always below atmospheric pressure during both inspiration and expiration (see Figure 2–11).

The pleural pressure, however, is not evenly distributed within the thorax. In the normal individual in the upright position, there is a natural pleural pressure gradient from the upper lung region to the lower. The negative pleural pressure at the apex of the lung is normally greater (from −7 to −10 cm H_2O pressure) than at the base (from −2 to −3 cm H_2O pressure). This gradient is gravity dependent and is thought to be due to the normal weight distribution of the lungs above and below the hilum. In other words, because the lung is suspended from the hilum, and because the lung base weighs more than the apex (primarily due to the increased blood flow in the lung base), the lung base requires more pressure for support than does the lung apex. This causes the negative pleural pressure around the lung base to be less.

Because of the greater negative pleural pressure in the upper lung regions, the alveoli in those regions are expanded more than the alveoli in the lower regions. In fact, many of the alveoli in the upper lung regions may be close to, or at, their total filling capacity. This means, therefore, that the compliance of the alveoli in the upper lung regions is normally less than the compliance of the alveoli in the lower lung regions in the normal person in the upright position. As a result, during inspiration the alveoli in the upper lung regions are unable to accommodate as much gas as the alveoli in the lower lung regions. Thus, in the normal individual in the upright position, ventilation is usually much greater and more effective in the lower lung regions (Figure 2–56).

FIGURE 2-56 Intrapleural pressure gradient in the upright position. The negative intrapleural pressure normally is greater in the upper lung regions compared with the lower lung regions. Because of this, the alveoli in the upper lung regions expand more than those in the lower lung regions. This condition causes alveolar compliance to be lower in the upper lung regions and ventilation to be greater in the lower lung regions.



The Effect of Airway Resistance and Lung Compliance on Ventilatory Patterns

As already mentioned, the respiratory rate and tidal volume presented by an individual are known as the *ventilatory pattern*. The average normal ventilatory pattern is a respiratory rate of 15 breaths per minute and a tidal volume of about 500 mL. Although the precise mechanism is not clear, it is well documented that these ventilatory patterns frequently develop in response to changes in lung compliance and airway resistance.

Clinical Connection 2-20

How the Adopted Breathing Pattern Changes in Chronic Obstructive Lung Disorders When Compromised by a Restrictive Lung Disorder

The patient's adopted ventilatory pattern is frequently modified in the clinical setting because of secondary complications. For example, a patient with emphysema (chronic obstructive lung disorder), who has adopted a decreased ventilatory rate and an increased tidal volume because of the increased

Clinical Connection 2-20, Continued

R_{aw} and increased time constant associated with the disorder, may in fact demonstrate an increased ventilatory rate and decreased tidal volume in response to a lung infection (pneumonia) that causes lung compliance to decrease.

As will be discussed later in Chapter 7, because acute ventilatory changes (i.e., hyperventilation or hypoventilation) are commonly seen in patients who have chronic obstructive pulmonary disorders, the respiratory therapist must be familiar with—and on the alert for—clinical signs and symptoms that indicate the patient's ventilatory status is changing from their normal. For example, an arterial blood gas on the patient with chronic obstructive pulmonary disease often confirms the patient is hyperventilating—that is, breathing faster than his or her normal—because of a secondary pneumonia. Clinically, this arterial blood gas is classified as "acute alveolar hyperventilation superimposed on chronic ventilatory failure"[8] and, importantly, the patient is in "impending ventilatory failure." The reader will learn more about these interesting arterial blood gas measurements later in the textbook.

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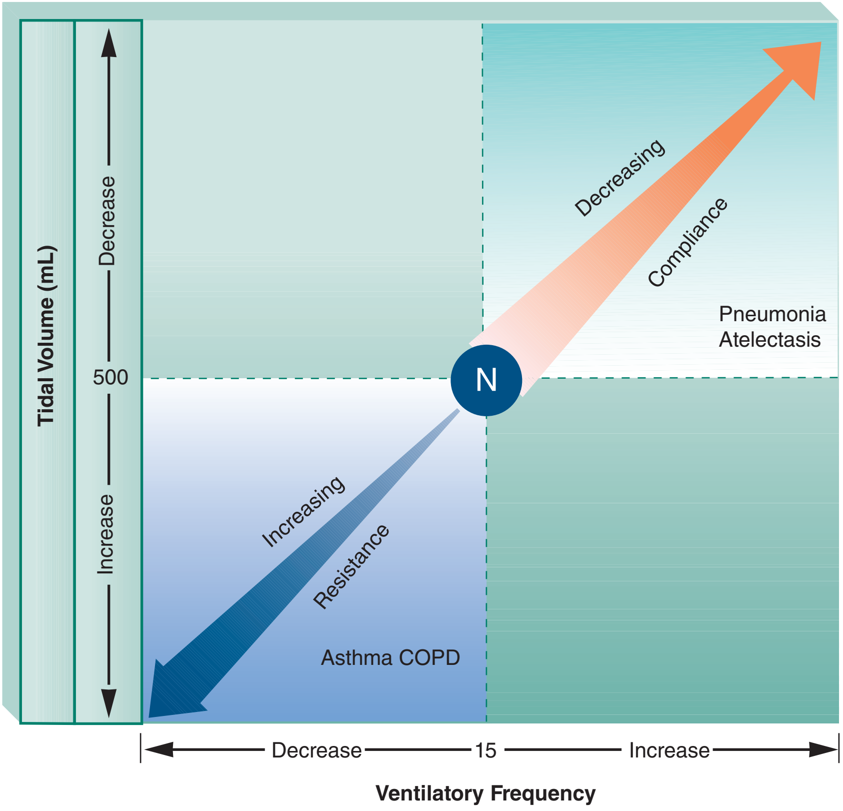
[8] Clinically, this arterial blood gas (ABG) is also called acute hyperventilation superimposed on compensated respiratory acidosis. The importance of arterial blood gas interpretations will be discussed in greater detail in Chapter 7: Acid–Base Balance and Regulation.

When lung compliance decreases, the patient's ventilatory rate generally increases while, at the same time, the tidal volume decreases. When airway resistance increases, the patient's ventilatory frequency usually decreases while, at the same time, the tidal volume increases (Figure 2–57).

FIGURE 2-57 The effects of increased airway resistance and decreased lung compliance on ventilatory frequency and tidal volume.

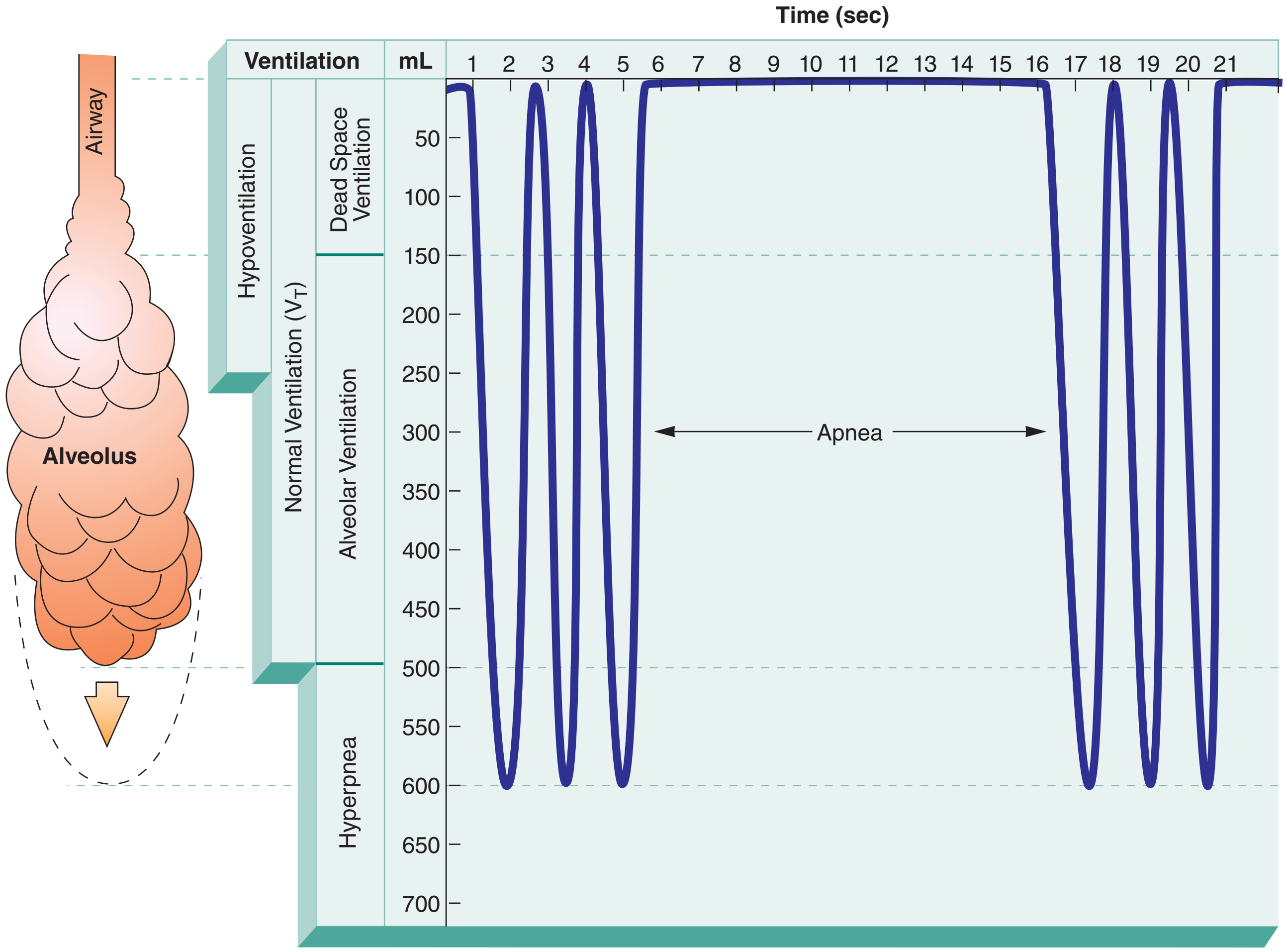


The ventilatory pattern is determined by both **ventilatory efficiency** (to minimize dead space ventilation) and **metabolic efficiency** (to minimize the work or oxygen cost of breathing). The body is assumed to adjust both rate and depth of breathing to give the best trade-off between the two. In severe cases, an increase in ventilation will ultimately reach a point in which the increase in oxygen delivery is exceeded by the increase in oxygen demanded by the respiratory muscles. In short, the ventilatory pattern adopted by a patient is based on minimum work requirements, rather than ventilatory efficiency.

In physics, work is defined as the force applied multiplied by the distance moved (work = force × distance). In respiratory physiology, the changes in transpulmonary pressure (force) multiplied by the change in lung volume (distance) may be used to quantitate the amount of work required to breathe (work = pressure × volume). Normally, about 5 percent of an individual's total energy output goes to the work of breathing.

Thus, because the patient may adopt a ventilatory pattern based on the **expenditure of energy** rather than the efficiency of ventilation, it cannot be assumed that the ventilatory pattern acquired by the patient in response to a certain respiratory disorder is the most efficient one in terms of physiologic gas exchange. Such ventilatory patterns are usually seen in the more severe pulmonary disorders that cause lung compliance to decrease or airway resistance to increase.

FIGURE 2-58 Biot's breathing: Short episodes of rapid, uniformly deep inspirations, followed by 10 to 30 seconds of apnea.



Overview of Specific Breathing Conditions

The following are types of breathing conditions frequently seen by the respiratory therapist in the clinical setting.

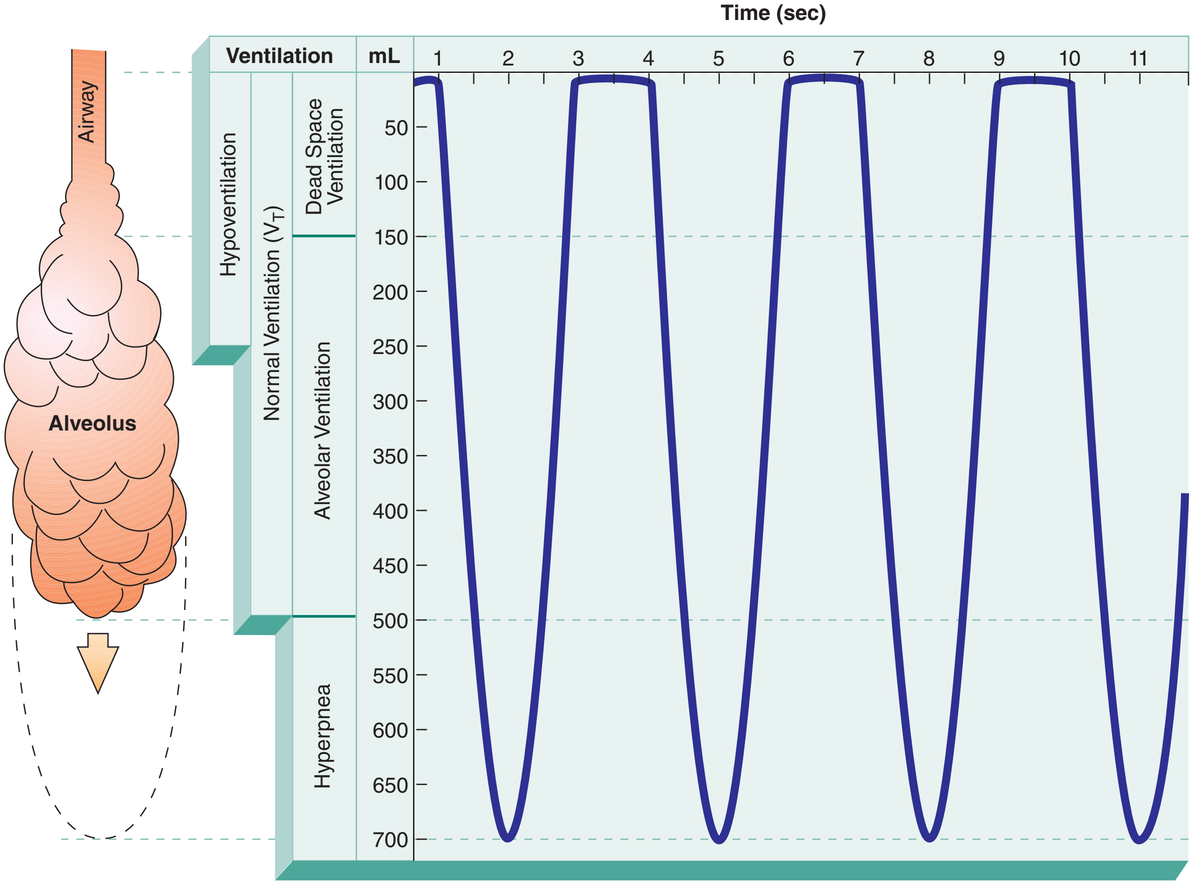
Apnea: Complete absence of spontaneous ventilation. This causes the PA_{O_2}[9] and PA_{O_2}[10] to rapidly decrease and the PA_{CO_2}[11] and Pa_{CO_2}[12] to increase. Death will ensue in minutes.

Eupnea: Normal, spontaneous breathing (see Figure 2–50).

Biot's breathing: Short episodes of rapid, uniformly deep inspirations, followed by 10 to 30 seconds of apnea (Figure 2–58). This pattern was first described in patients suffering from meningitis.

Hyperpnea: Increased depth (volume) of breathing with or without an increased frequency (Figure 2–59).

FIGURE 2-59 Hyperpnea: Increased depth of breathing.



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[9] PA_{O_2} 5 *alveolar oxygen tension.*
[10] Pa_{O_2} 5 *arterial oxygen tension.*
[11] PA_{CO_2} 5 *alveolar carbon dioxide tension.*
[12] Pa_{CO_2} 5 *arterial carbon dioxide tension.*

Hyperventilation: Increased alveolar ventilation (produced by any ventilatory pattern that causes an increase in either the ventilatory rate or the depth of breathing) that causes the PA_{CO_2} and, therefore, the Pa_{CO_2} to decrease (Figure 2–60).

Hypoventilation: Decreased alveolar ventilation (produced by any ventilatory pattern that causes a decrease in either the ventilatory rate or the depth of breathing) that causes the PA_{CO_2} and, therefore, the Pa_{CO_2} to increase (Figure 2–61).

Tachypnea: A rapid rate of breathing.

Cheyne-Stokes breathing: Ten to 30 seconds of apnea, followed by a gradual increase in the volume and frequency of breathing, followed by a gradual decrease in the volume of breathing until another period of apnea occurs (Figure 2–62). As the depth of breathing increases, the PA_{CO_2} and Pa_{CO_2} fall and the PA_{O_2} and Pa_{O_2} rise. Cheyne-Stokes breathing is associated with cerebral disorders and congestive heart failure (CHF).

FIGURE 2-60 Hyperventilation: Increased rate (A) or depth (B), or some combination of these, of breathing that causes the PA_{CO_2} and, therefore, the Pa_{CO_2} to decrease.

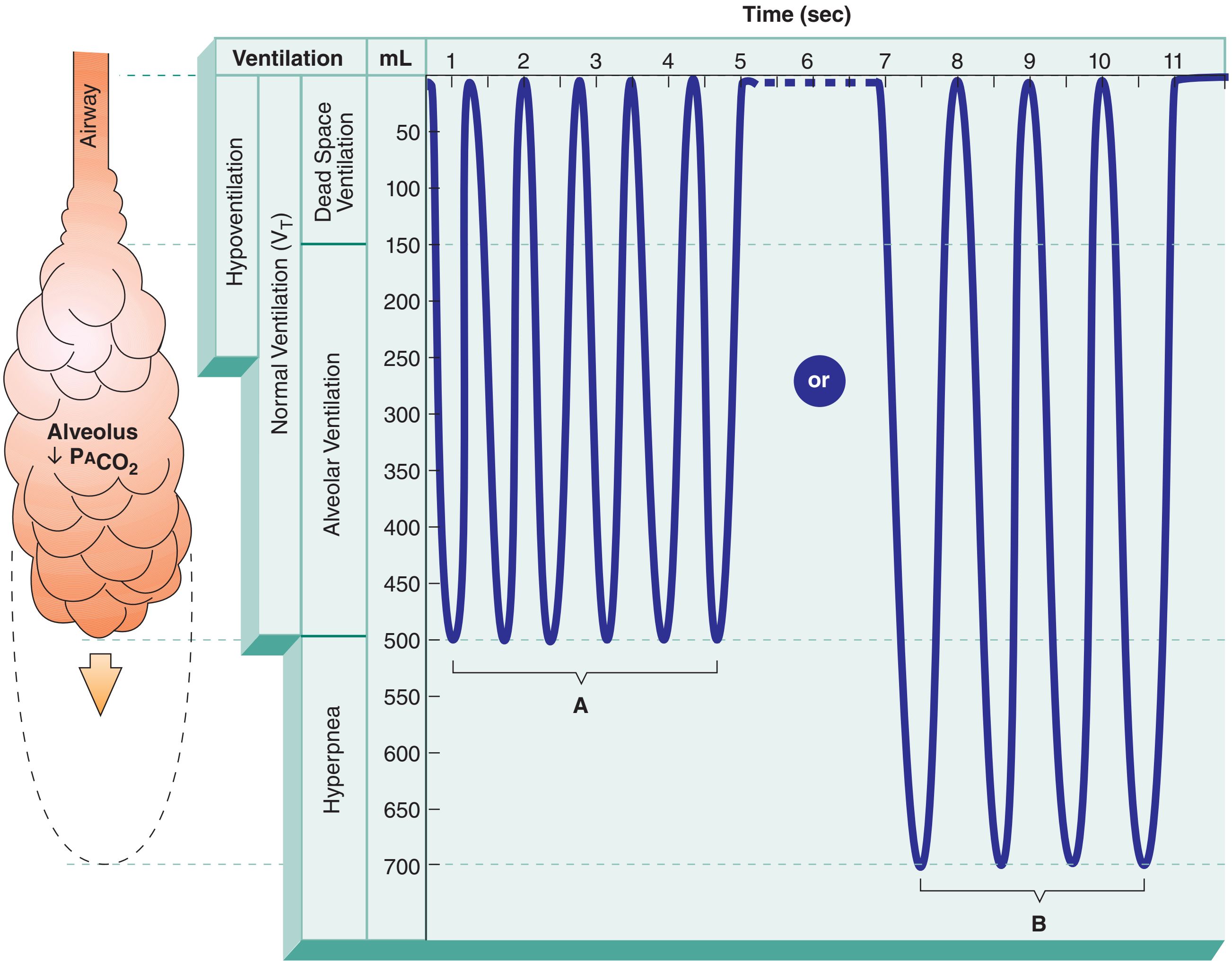
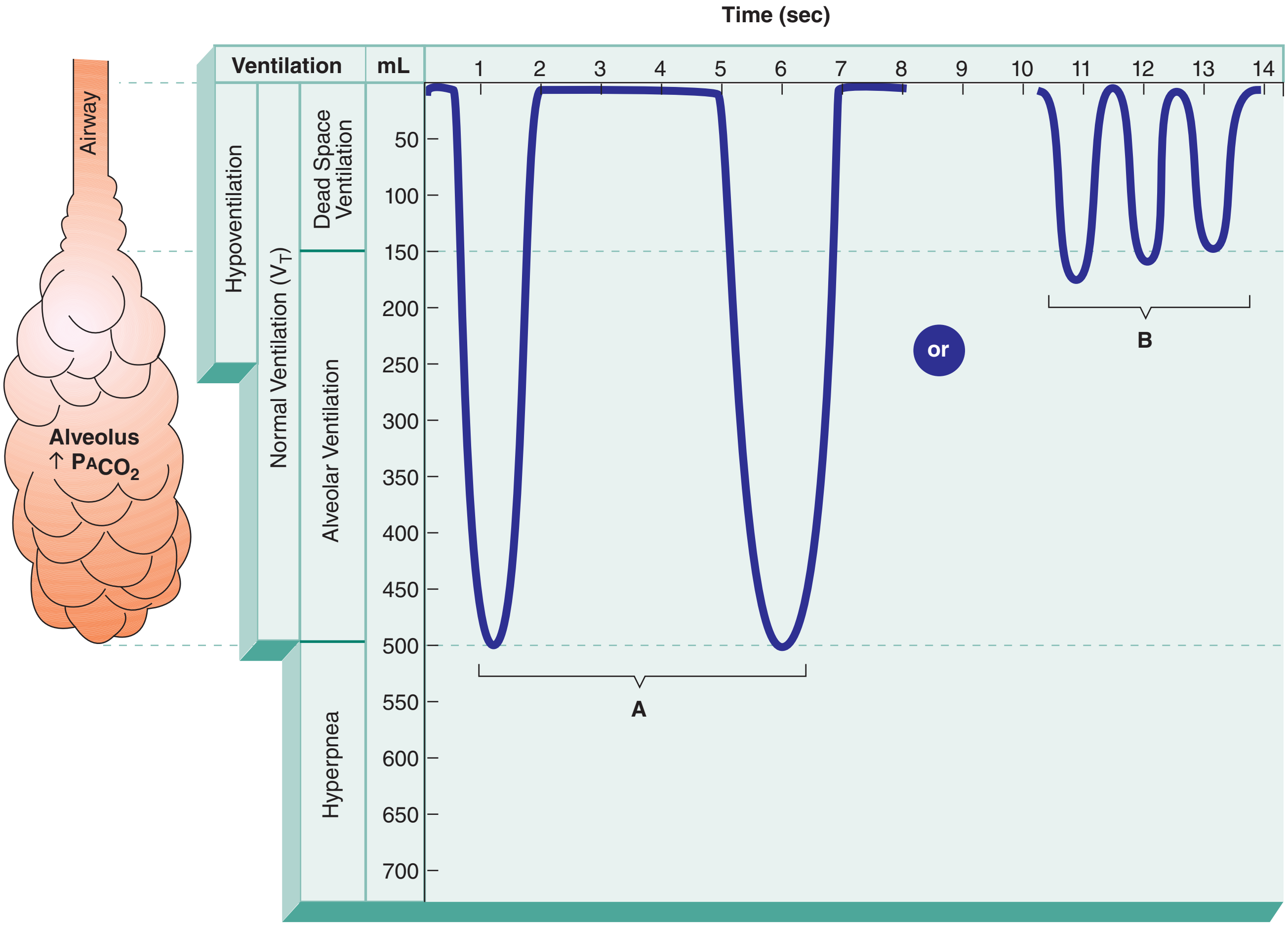

Time (sec)
Ventilation
mL
1
2
3
4
5
6
7
8
9
10
11
Airway
Hypoventilation
Normal Ventilation (V_T)
Dead Space Ventilation
Alveolar Ventilation
Hyperpnea
50
100
150
200
250
300
350
400
450
500
550
600
650
700
Alveolus
↓ PA_{CO_2}
or
A
B

FIGURE 2-61 Hypoventilation: Decreased rate (A) or depth (B), or some combination of both, of breathing that causes the $P_{A_{CO_2}}$ and, therefore, the Pa_{CO_2} to increase.



Clinical Connection 2-21

The Arterial Carbon Dioxide Level and Its Relationship to the Clinical Confirmation of Hyperventilation and Hypoventilation

A patient's breathing rate can often be misleading. For example, even though a fast respiratory rate is often associated with hyperventilation, the patient's rapid breathing rate alone is not enough to make the assessment of hyperventilation. The absolute confirmation of hyperventilation can only be made by evaluating the patient's arterial carbon dioxide partial pressure (Pa_{CO_2}). Hyperventilation is verified when the patient's arterial blood gas values reveal an acute respiratory alkalosis (increased pH) as a result of a sudden decrease in the Pa_{CO_2} level. On the other hand, hypoventilation is established when the arterial blood gas values show an acute respiratory acidosis (decreased pH) as a result of an elevated Pa_{CO_2} level.

(*Continued*)

Clinical Connection 2-21, Continued

In the clinical setting, the respiratory therapist frequently evaluates the patient's arterial blood gas values—pH, Pa_{CO_2}, HCO_3^-, and Pa_{O_2}—to determine the patient's ventilatory status. Oftentimes, the therapist must adjust the rate and tidal volume on the mechanical ventilator to correct the patient's Pa_{CO_2} level. The importance of the Pa_{CO_2} and its relationship to arterial blood gas interpretations will be discussed in greater detail in Chapter 7: Acid–Base Balance and Regulation.

Kussmaul's breathing: Both an increased depth (hyperpnea) and rate of breathing (Figure 2–63). This ventilatory pattern causes the $P_{A_{CO_2}}$ and Pa_{CO_2} to decline and the $P_{A_{CO_2}}$ and Pa_{O_2} to increase. Kussmaul's breathing is commonly associated with diabetic acidosis (ketoacidosis).

Orthopnea: A condition in which an individual is able to breathe most comfortably only in the upright position.

Dyspnea: Difficulty in breathing, of which the individual is aware.

Agonal respirations: Gasping respirations or agonal breathing is an abnormal brainstem reflex breathing pattern characterized by gasping, labored breathing, accompanied by strange vocalizations and myoclonus (i.e., a brief involuntary twitching of a muscle or a group of muscles). Possible causes include cerebral ischemia or extreme hypoxia.

FIGURE 2-62 Cheyne-Stokes breathing: a gradual increase and decrease in the volume and rate of breathing, followed by 10 to 30 seconds of apnea.

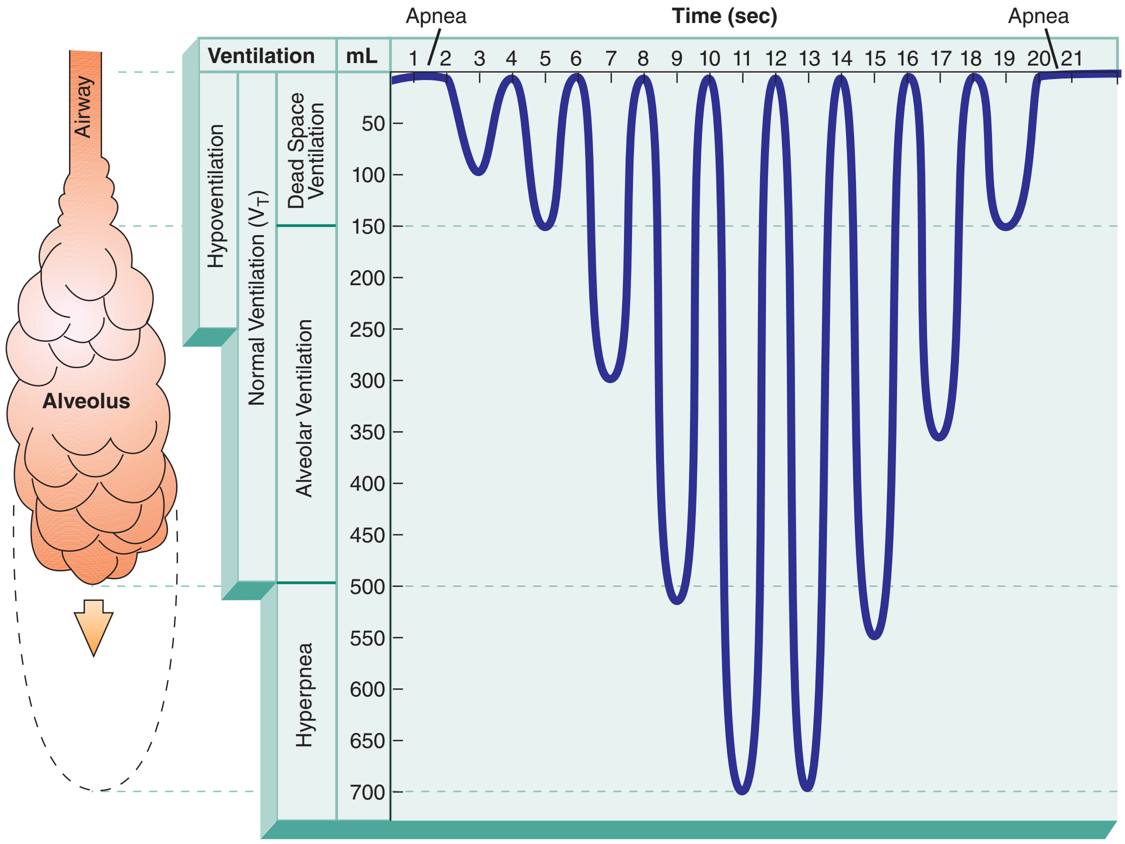
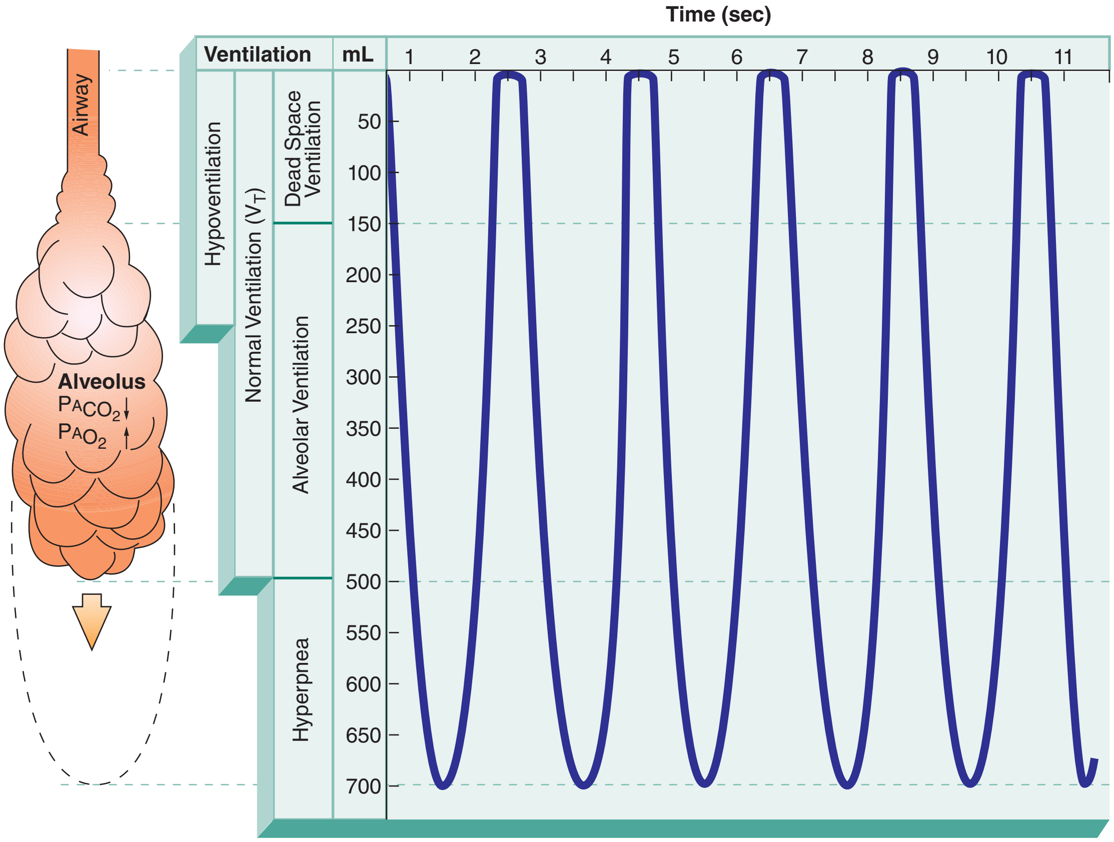


FIGURE 2-63 Kussmaul's breathing: increased rate and depth of breathing. This breathing pattern causes the $P_{A_{CO_2}}$ and Pa_{CO_2} to decrease and $P_{A_{O_2}}$ and Pa_{O_2} to increase.



Chapter Summary

The essential knowledge base for ventilation consists of four major areas. *First,* the respiratory therapist must understand the primary mechanisms of pulmonary ventilation. Important to this subject includes how the atmosphere pressure, Boyle's law, and pressure gradients are connected to (1) the excursion of the diaphragm; (2) pleural pressure; (3) intra-alveolar pressure; and (4) gas flow during inspiration, end-inspiration, expiration, and end-expiration. In addition, key pressure gradients related to the mechanisms of ventilation are the driving pressure, transrespiratory pressure, transmural pressure, transpulmonary pressure, and transthoracic pressure. Clinical connections associated with the mechanisms of ventilation include inspiratory intercostal retractions and the harmful effects of pressure gradients when the thorax is unstable.

Second, the respiratory therapist must understand the elastic properties of the lungs. Major components of this subject are (1) lung compliance, including the calculation of lung compliance; (2) elastance, including Hooke's law; and (3) surface tension and its relationship to Laplace's law, pulmonary surfactant, and the deficiency of pulmonary surfactant. Clinical connections associated with all the above topics include (1) pulmonary disorders that force the patient to breathe at the top—flat portion—of the pressure-volume curve; (2) pulmonary disorders that shift the pressure-volume curve to the right—decreased lung compliance; (3) positive-pressure ventilation and related hazards; (4) negative-pressure ventilation; and (5) pulmonary surfactant deficiency.

Third, the therapist must have a good understanding of the dynamic characteristics of the lungs. This important subject includes (1) how Poiseuille's law arranged for either flow or pressure relates to the radius of the bronchial airways; (2) airway resistance, including its calculation, and its relationship to laminar and turbulent flow; and (3) dynamic compliance and its relationship to increased airway resistance and frequency dependence. Clinical connections associated with these topics include (1) respiratory disorders that decrease the radius of the airways; (2) restrictive lung disorders, time constants, and breathing pattern relationships; (3) obstructive lung disorders, time constants, and breathing pattern relationships; and (4) auto-PEEP and its relationship to airway resistance during rapid ventilatory rates.

Finally, the respiratory therapist needs a good knowledge base of the characteristics of normal and abnormal ventilatory patterns. This subject consists of (1) knowing the meaning of the normal ventilatory pattern, including the tidal volume, ventilatory rate, and IE ratio; (2) differentiating between alveolar ventilation and dead space ventilation; (3) knowing how the depth and rate of breathing affects alveolar ventilation; (4) being able to calculate an individual's alveolar ventilation; (5) understanding how the normal pleural pressure differences cause regional differences in normal lung ventilation; (6) knowing how the respiratory rate and tidal volume change in response to a decreased lung compliance or an increased airway resistance; and (7) the ability to recognize specific breathing conditions, such as Biot's breathing, hypoventilation, tachypnea, Cheyne-Stokes breathing, Kussmaul's breathing, orthopnea, and dyspnea.

Clinical connections associated with these topics include (1) inspiratory intercostal retraction; (2) abdominal paradox (diaphragm fatigue); (3) the harmful effects of pressure gradients when the thorax is unstable; (4) pulmonary disorders that force the patient to breathe at the top—flat portion—of the pressure-volume curve; (5) pulmonary disorders that shift the pressure-volume curve to the right; (6) positive-pressure ventilation; (7) hazards of positive-pressure ventilation; (8) negative-pressure ventilation; (9) pulmonary surfactant deficiency; (10) respiratory disorders that decrease the radius of the airways; (11) endotracheal size and Poiseuille's law; (12) restrictive lung disorders, time constants, and breathing pattern relationships; (13) obstructive lung disorders, time constants, and breathing pattern relationships; (14) Auto-PEEP and its relationship to airway resistance during rapid ventilatory rates; (15) normal respiratory rates for different age groups; (16) tidal volume and breathing rate strategies for mechanical ventilation; (17) dead space ventilation associated with the snorkel; (18) a giraffe's neck: alveolar ventilation versus dead space ventilation; (19) pulmonary embolus and dead space; (20) how the adopted breathing patterns changes ion chronic obstructive lung disorders when compromised by a restrictive lung disorder; and (21) the arterial carbon dioxide level and its relationship to the clinical verification of hyperventilation and hypoventilation.

1 Clinical Application Case

A 22-year-old male who had been in a motorcycle crash was brought to the emergency department with several facial, neck, and shoulder abrasions and lacerations, and multiple broken ribs. During each breath, the patient's right anterior chest moved inward during inspiration and outward during exhalation (clinically this is called a *flail chest*). The patient was alert, in pain, and stated, "I can't breathe. Am I going to die?"

The patient's skin was pale and blue. His vital signs were blood pressure—166/93 mm Hg, heart rate—135 beats/min, and respiratory rate—26 breaths/min and shallow. While on a simple oxygen mask, the patient's peripheral oxygen saturation level Sp_{O_2}, measured over the skin of his index finger, was 79 percent (normal, 97 percent). Chest X-ray showed that the third, fourth, fifth, sixth, and seventh ribs were each broken in two or three places on the right anterior chest. The chest X-ray also revealed that his right lung was partially collapsed.

A chest tube was inserted, and the patient was immediately transferred to the intensive care unit (ICU), sedated, intubated, and placed on a mechanical ventilator. The mechanical ventilator was set at a ventilatory

Clinical Application Case 1 (continued)

rate of 12 breaths/minute, an oxygen concentration of 0.5, and a positive end-expiratory pressure (PEEP) of +5 cm H_2O.[13] No spontaneous breaths were present between the mandatory mechanical breaths.

Four hours later, the patient appeared comfortable and his skin color was normal. The ventilator was set at a rate of 12 breaths/min, an inspired oxygen concentration $F_{I_{O_2}}$ of 0.3, and a PEEP of +5 cm H_2O. No spontaneous breaths were generated between each mechanical ventilation. During each mechanical breath, both the right and left side of the patient's chest expanded symmetrically. His blood pressure was 127/83 mm Hg and heart rate was 76 beats/min. A second chest X-ray revealed that his right lung had re-expanded. His peripheral oxygen saturation level was 97 percent.

Discussion

This case illustrates (1) the effects on *transthoracic pressure and transpulmonary pressure* when the thorax is unstable, (2) how the excursions of the diaphragm affect the pleural pressure, (3) acute decreased lung compliance, and (4) the therapeutic effects of positive-pressure ventilation in flail chest cases.

Under normal conditions, on each inhalation, the diaphragm moves downward and causes the pleural pressure and alveolar pressure to decrease (see Figure 2–11). In this case, however, the patient's ribs were broken on the right side and caved in during each inspiration when the pleural and alveolar pressure decreased. This caused the right lung to partially collapse—an acute decreased lung compliance condition (see Figure 2–19).

This process was corrected when the patient was ventilated with positive pressure. The patient no longer had to generate negative pressure to inhale. During each positive-pressure breath, the chest wall expanded evenly and returned to normal resting level at the end of each expiration. This process allowed the ribs to heal. After 10 days, the patient was weaned from the ventilator. He was discharged 3 days later.

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[13] At the end of a normal spontaneous expiration, the pressure in the alveoli is equal to the barometric pressure. A 15 cm H_2O of PEEP means that at the end of each exhalation, the patient's alveoli still had a positive pressure of 5 cm H_2O above atmospheric pressure. Therapeutically, this helps to re-expand collapsed alveoli or prevent the collapse of alveoli.

2 Clinical Application Case

This 14-year-old girl with a long history of asthma presented in the emergency department in moderate to severe respiratory distress. She appeared very frightened and tears were running down her face. She was sitting perched forward with her arms braced in a tripod-like position on the side of a gurney, hands clutching the edge of the gurney. She was using her accessory muscles of inspiration. When asked about her condition, she stated, "I can't get enough air." She could only speak two or three words at a time, between each breath.

The patient's skin appeared pale and bluish. She had a frequent and strong cough, productive of large amounts of thick, white secretions. Her vital signs were blood pressure—151/93 mm Hg, heart rate—106 beats/min and strong, and respiratory rate—32 breaths/min. Wheezes were heard over both lung fields. Chest X-ray showed that her lungs were hyperinflated and that her diaphragm was depressed. Her peripheral oxygen saturation level Sp_{O_2}, measured by pulse oximetry over the skin of her index finger, was 89 percent (normal, 97 percent).

The respiratory therapist working in the emergency department started the patient on oxygen via a 6 L/min nasal cannula, and on a bronchodilator continuously, via a handheld aerosol. The therapist also remained at the patient's bedside to monitor the patient's response to treatment and to encourage the patient to take slow, deep inspirations.

(*continued*)

Clinical Application Case 2 (continued)

Forty-five minutes later, the patient had substantially improved. She was sitting up in bed and no longer appeared to be in respiratory distress. She could speak in longer sentences without getting short of breath. Her skin color was normal. Her vital signs were blood pressure—126/83 mm Hg, heart rate—87 beats/min, and respiratory rate—14 breaths/min.

When instructed to cough, she generated a strong, nonproductive cough. Although wheezes could still be heard over the patient's lungs, they were not as severe as they were on admission. A second chest X-ray showed that her lungs were normal and her diaphragm was no longer depressed. Her Sp_{O_2} was 94 percent.

Discussion

This case illustrates (1) an acute decreased lung compliance condition, (2) how *Poiseuille's law* can be used to demonstrate the effects of bronchial constriction and excessive airway secretions on bronchial gas flow and the work of breathing, (3) the effects of an increased *airway resistance* (R_{aw}) on *time constants,* and (4) the *frequency-dependent* effects of a decreased ventilatory rate on the ventilation of alveoli.

As the severity of the tracheobronchial tree constriction progressively increased, the patient's ability to exhale fully declined. This process caused the patient's lungs to hyperinflate (but not with fresh air). As a result of the hyperinflation, the patient's work of breathing increased, because her lungs were functioning at the very top of their pressure-volume curve—the flat portion of the curve (see Figure 2–21). As the pressure-volume curve shows, lung compliance is low on the upper, flat portion of the pressure-volume curve. Because of this, the patient was working extremely hard to breathe (i.e., generating large pleural pressure changes), with little or no change in her alveolar ventilation (volume), as shown in Figure 2–21.

In addition, as Poiseuille's law demonstrates, the tracheobronchial tree constriction and excessive airway secretions, both caused by the asthma attack, can have a tremendous impact on gas flow and on the patient's work of breathing. Poiseuille's law shows that gas flow is *directly* related to the fourth power of the radius (r^4) of the tracheobronchial tree, and pressure (e.g., pleural pressure changes) is *indirectly* related to the fourth power of the radius of the airways. Thus, if the patient's bronchial constriction and bronchial secretions decreased the radius of the airways by one half, the flow of gas would decrease to $\frac{1}{16}$ of the original flow (see Figure 2–40). Similarly, for the patient to maintain the same flow rate, she would have to increase her work of breathing to 16 times her original level (see Figure 2–42).

Airway resistance (R_{aw}) can be defined as the pleural pressure difference (ΔP) generated by the patient to move a volume of gas divided by the flow rate ($\dot{V}$). Again, according to Poiseuille's law, it can be seen that as the airways narrow, pleural pressure will increase significantly while, at the same time, gas flow through the airways will decrease. Because $R_{aw} = \Delta P \div \dot{V}$, it is easy to see mathematically how quickly airway resistance can increase during an asthmatic episode.

Finally, as the airway resistance (R_{aw}) increased, the alveoli distal to the bronchial constriction required a longer time to inflate. These alveoli are said to have a long *time constant* (see Figure 2–46). A product of the time constants is the measurement called *dynamic compliance,* which is the change in volume of the lungs divided by the change in the transpulmonary pressure during the time required for one breath (i.e., during a period of gas flow).

In the healthy lung, the dynamic compliance is approximately equal to lung compliance at all breathing frequencies. In the patient with partially obstructed airways, however, the ratio of dynamic compliance to lung compliance decreases as the respiratory rate increases. The alveoli distal to the airway obstruction do not have enough time to fully inflate as the breathing frequency rises. The compliance of these alveoli is said to be *frequency dependent.* This is why it was important for the respiratory therapist to remain at the bedside and encourage the patient to take slow, deep breaths.

Because the patient was having trouble inhaling a normal volume of gas and because her oxygen saturation level Sp_{O_2} was below normal, oxygen therapy was clearly indicated. The continuous bronchodilator therapy was also indicated and worked to offset the effects of airway constriction (as described by Poiseuille's law), increased airway resistance, air trapping, and hyperinflation. As the lung hyperinflation progressively declined, lung compliance steadily increased, or returned to normal (i.e., returned back to the steep portion of the pressure-volume curve). The patient continued to improve and was discharged from the hospital by the next afternoon.

Review Questions

1. **The average compliance of the lungs and chest wall combined is**

A. 0.1 L/cm H_2O.
B. 0.2 L/cm H_2O.
C. 0.3 L/cm H_2O.
D. 0.4 L/cm H_2O.

2. **Normally, the airway resistance in the tracheobronchial tree is about**

A. 0.5–1.5 cm H_2O/L/sec.
B. 1.0–2.0 cm H_2O/L/sec.
C. 2.0–3.0 cm H_2O/L/sec.
D. 3.0–4.0 cm H_2O/L/sec.

3. **In the normal individual in the upright position**

1. the negative pleural pressure is greater (i.e., more negative) in the upper lung regions.
2. the alveoli in the lower lung regions are larger than the alveoli in the upper lung regions.
3. ventilation is more effective in the lower lung regions.
4. the pleural pressure is always below atmospheric pressure during a normal ventilatory cycle.
   A. 1 and 2 only
   B. 2 and 3 only
   C. 2, 3, and 4 only
   D. 1, 3, and 4 only

4. **When lung compliance decreases, the patient commonly has**

1. an increased ventilatory rate.
2. a decreased tidal volume.
3. an increased tidal volume.
4. a decreased ventilatory rate.
   A. 1 only
   B. 2 only
   C. 3 and 4 only
   D. 1 and 2 only

5. **When arranged for flow Poiseuille's law states that flow is**

1. inversely proportional to r^4.
2. directly proportional to P.
3. inversely proportional to η.
4. directly proportional to l.
   A. 1 only
   B. 2 only
   C. 2 and 3 only
   D. 3 and 4 only

6. **During a normal exhalation, the**

1. intra-alveolar pressure is greater than the atmospheric pressure.
2. pleural pressure is less than the atmospheric pressure.
3. intra-alveolar pressure is in equilibrium with the atmospheric pressure.
4. pleural pressure progressively decreases.
   A. 1 only
   B. 4 only
   C. 1 and 2 only
   D. 3 and 4 only

7. **At rest, the normal pleural pressure change during quiet breathing is about**

A. 0–2 mm Hg.
B. 2–4 mm Hg.
C. 4–6 mm Hg.
D. 6–8 mm Hg.

8. **Normally, an individual's tidal volume is about**

A. 1–2 mL/1b.
B. 3–4 mL/1b.
C. 5–6 mL/1b.
D. 7–8 mL/1b.

9. **A rapid and shallow ventilatory pattern is called**

A. hyperpnea.
B. apnea.
C. alveolar hyperventilation.
D. tachypnea.

10. **Assuming that pressure remains constant, if the radius of a bronchial airway through which gas flows at a rate of 400 L/min is reduced to one-half of its original size, the flow through the bronchial airway would change to**

A. 10 L/min.
B. 25 L/min.
C. 100 L/min.
D. 200 L/min.

11. **The difference between the alveolar pressure and the pleural pressure is called the**

A. transpulmonary pressure.
B. transthoracic pressure.
C. driving pressure.
D. transrespiratory pressure.

12. **According to Laplace's law, if a bubble with a radius of 4 cm and a distending pressure of 10 cm H_2O is reduced to a radius of 2 cm, the new distending pressure of the bubble will be**

A. 5 cm H_2O.
B. 10 cm H_2O.
C. 15 cm H_2O.
D. 20 cm H_2O.

13. **If alveolar unit A has one-half the compliance of alveolar unit B, then the**

1. time constant of unit A is essentially the same as that of unit B.
2. volume in unit B is two times greater than volume in unit A.
3. time constant of unit B is twice as long as that of unit A.
4. volume in unit B is essentially the same as the volume of unit A.
   A. 1 only
   B. 3 only
   C. 4 only
   D. 2 and 3 only

14. **If a patient weighs 175 pounds and has a tidal volume of 550 mL and a respiratory rate of 17 breaths/min, what is the patient's minute alveolar ventilation?**

____

15. **Lung compliance study**

Part I: If a patient generates a negative pleural pressure change of −8 cm H_2O during inspiration, and the lungs accept a new volume of 630 mL, what is the compliance of the lungs?

____

Part II: If the same patient, 6 hours later, generates a pleural pressure of −12 cm H_2O during inspiration, and the lungs accept a new volume of 850 mL, what is the compliance of the lungs?

____

Part III: In comparing Part II to Part I, the patient's lung compliance is

A. increasing.
B. decreasing.

16. **If a patient produces a flow rate of 5 L/sec during a forced exhalation by generating a transrespiratory pressure of 20 cm H_2O, what is the patient's R_{aw}?**

A. 1 cm H_2O/L/sec
B. 2 cm H_2O/L/sec
C. 3 cm H_2O/L/sec
D. 4 cm H_2O/L/sec

17. **As R_{aw} increases, the patient commonly manifests**

1. a decreased ventilatory rate.
2. an increased tidal volume.
3. a decreased tidal volume.
4. an increased ventilatory rate.
   A. 1 only
   B. 2 only
   C. 1 and 2 only
   D. 3 and 4 only

18. **If the radius of a bronchial airway, which has a driving pressure of 2 mm Hg, is reduced by 16 percent of its original size, what will be the new driving pressure required to maintain the same gas flow through the bronchial airway?**

A. 4 mm Hg
B. 8 mm Hg
C. 12 mm Hg
D. 16 mm Hg

19. **In the healthy lung, when the alveolus decreases in size during a normal exhalation, the**

1. surface tension decreases.
2. surfactant to alveolar surface area increases.
3. surface tension increases.
4. surfactant to alveolar surface area decreases.
   A. 1 only
   B. 3 only
   C. 4 only
   D. 1 and 2 only

20. **At end-expiration, P_{ta} is**

A. 0 mm Hg.
B. 2 mm Hg.
C. 4 mm Hg.
D. 6 mm Hg.

Clinical Application Questions

Case 1

1. Because this patient's ribs were broken on the right side, his right chest (bulged outward __________; caved inward __________) during each inspiration.
2. As a result of the previously described condition, the patient's right lung __________, which in turn caused an acute (decreased __________; increased __________) lung compliance condition.
3. The pathophysiologic process that developed in this case was corrected with __________. During each breath, the patient's chest wall (caved inward __________; moved outward __________) and then returned to normal __________ at the end of each expiration.

Case 2

1. As a result of the hyperinflation, the patient's work of breathing increased because her lungs were inflated to the very top of their pressure-volume curve. As the pressure-volume curve illustrates, lung compliance is very (high __________; low __________) on the upper, flat portion of the pressure-volume curve.
2. Because of the lung hyperinflation described in question 1, the patient was generating (small __________; large __________) pleural pressure changes with (little or no __________; moderate to large __________) volume changes.
3. What two major tracheobronchial tree changes occurred during the asthma attack that caused gas flow to significantly decrease, as described by Poiseuille's law?

   ____

   ____
4. As the airway resistance increased in this case, the alveoli distal to the bronchial constriction required (shorter __________; longer __________) time to inflate. These alveoli are said to have a (short __________; long __________) time constant.
5. A product of the time constants is the measurement called dynamic compliance, which is the change in volume of the lungs divided by the change in the transpulmonary pressure during the time for one breath. During an asthmatic episode, the patient's dynamic compliance (increases __________; decreases __________; remains the same __________).

g function
test

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CHAPTER 3

Pulmonary Function Measurements

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Define lung volumes and lung capacities.
2. Identify the approximate lung volumes and capacities in milliliters in the average healthy man and woman between 20 and 30 years of age.
3. Identify the lung volume and lung capacity changes that occur in obstruction and restrictive lung disorders.
4. Explain the dynamic flow rate measurements for the healthy man and woman between 20 and 30 years of age.
5. Discuss the factors that affect the normal predicted lung volumes and capacities.
6. Describe the effort-dependent and effort-independent portions of a forced expiratory maneuver.
7. Describe the effort-independent portion of a forced expiratory maneuver.
8. Describe the diffusion capacity of carbon monoxide study.
9. Describe how the patient's ability to maintain spontaneous, unassisted ventilation is evaluated.

Lung Volumes and Capacities

The volume of air that moves in and out of the lungs—and remains in the lungs—is a matter of great importance to the study of cardiopulmonary physiology. The total amount of air that the lungs can accommodate is divided into these two major categories—the **lung volumes** and **lung capacities**. There are four different lung volumes and four different lung capacities—which are composed of two or more lung volumes (Figure 3-1).

Lung Volumes

The four lung volumes are the tidal volume, inspiratory reserve volume, expiratory reserve volume, and residual volume. During normal quiet breathing, about 500 mL of air moves in and out of the lungs with each breath. This volume is **tidal volume (V_T)**. The amount of air that can be forcibly inhaled beyond the V_T is the **inspiratory reserve volume (IRV)**. The amount of air that can be forcibly exhaled after a normal V_T is the **expiratory reserve volume (ERV)**. The amount of air still in the lungs after a forced ERV is the **residual volume (RV)**. The RV is important for keeping the alveoli open and overall gas exchange. Table 3–1 provides a description of the lung volumes and the average normal values for males and females between 20 and 30 years of age.

FIGURE 3-1 Normal lung volumes and capacities. IRV = inspiratory reserve volume; V_T = tidal volume; ERV = expiratory reserve volume; RV = residual volume; VC = vital capacity; TLC = total lung capacity; IC = inspiratory capacity; FRC = functional residual capacity.

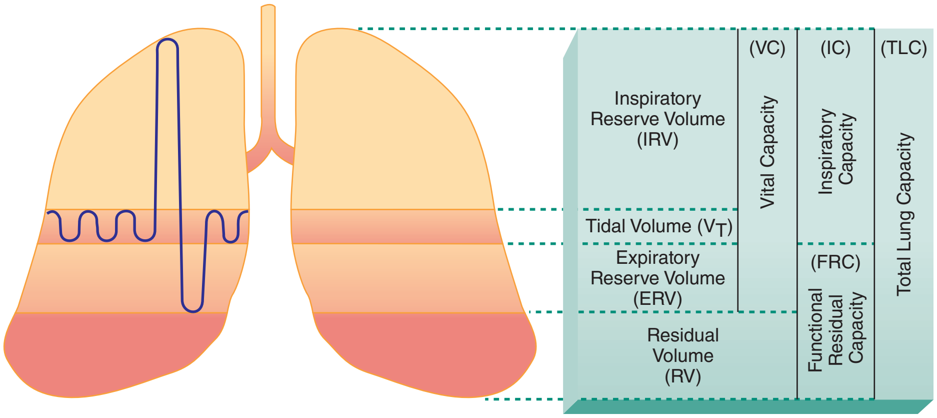

Inspiratory Reserve Volume (IRV)
Tidal Volume (V_T)
Expiratory Reserve Volume (ERV)
Residual Volume (RV)
(VC)
Vital Capacity
(IC)
Inspiratory Capacity
(FRC)
Functional Residual Capacity
(TLC)
Total Lung Capacity

TABLE 3-1 Approximate Lung Volumes and Capacities in Healthy Men and Women 20 to 30 Years of Age

	Measurement	Description	Adult Male Average Value	Adult Female Average Value
Lung Volumes	**Tidal volume (V_T)**	The amount of air inhaled and exhaled with each breath during quiet breathing	500 mL	400–500 mL
	Inspiratory reserve volume (IRV)	The amount of air that can be forcibly inhaled beyond the V_T	3100 mL	1900 mL
	Expiratory reserve volume (ERV)	The amount of air that can be forcibly exhaled after a normal V_T	1200 mL	800 mL
	Residual volume (RV)	The amount of air still in the lungs after a forced ERV	1200 mL	1000 mL
	Vital capacity (VC)	The maximum volume of air that can be exhaled after a maximal inspiration (VC = IRV + V_T + ERV).	4800 mL	3200 mL
Lung Capacities	**Inspiratory capacity (IC)**	The volume of air that can be inhaled after a normal exhalation (IC = V_T + IRV).	3600 mL	2400 mL
	Functional residual capacity (FRC)	The volume of air remaining in the lungs after a normal exhalation (FRC = ERV + RV).	2400 mL	1800 mL
	Total lung capacity (TLC)	The maximum amount of air that the lungs can accommodate (TLC = VT + IRV + ERV + RV).	6000 mL	4200 mL

Lung Capacities

The four lung capacities are the vital capacity, inspiratory capacity, functional residual capacity, and total lung capacity. The **vital capacity (VC)** is the maximum volume of air that can be exhaled after a maximal inspiration. The VC is the sum of the IRV + V_T + ERV. There are two major VC measurements: the **slow vital**

capacity (SVC), in which exhalation is performed slowly; and the **forced vital capacity (FVC)**, in which maximal effort is made to exhale as rapidly as possible. The FVC will be discussed in more detail later in this chapter.

The **inspiratory capacity (IC)** is the volume of air that can be inhaled after a normal exhalation. The IC is the sum of the V_T + IRV. The **functional residual capacity (FRC)** is the volume of air remaining in the lungs after a normal exhalation. The FRC is the sum of the ERV + RV. The total lung capacity (TLC) is the maximum amount of air that the lungs can accommodate. The TLC is the sum of the V_T + IRV + ERV + RV. Table 3–1 provides a description of the lung capacities and the average normal values for males and females between 20 and 30 years of age.

Lung Volumes and Capacities in Obstructive and Restrictive Lung Disorders

The lung volumes and lung capacities are abnormally altered in any respiratory disorder to some degree. Pulmonary function studies are routinely administered to these patients to (1) determine if the lung problem is an obstructive or restrictive lung disorder, (2) evaluate the severity of the pulmonary disorder, (3) determine if the lung problem is an obstructive or restrictive lung disorder, and (4) monitor the progress of chronic pulmonary disorders.

In an **obstructive lung disorder**, the RV, V_T, and FRC are increased; and the VC, IC, IRV, and ERV are decreased (Figure 3–2). In a **restrictive lung disorder**, the VC, IC, RV, FRC, V_T, and TLC are all decreased (Figure 3–3). Relative to the degree of severity, both an obstructive or a restrictive lung disorder disrupt the exchange of oxygen and carbon dioxide between the alveoli and pulmonary capillary blood.

Indirect Measurements of the Residual Volume and Capacities Containing the Residual Volume

Because the *residual volume* (RV) cannot be exhaled, the RV, and lung capacities that contain the RV, is measured indirectly by one of the following methods: *closed-circuit helium dilution, open-circuit nitrogen washout,* or *body plethysmography.* A brief description of each of these methods follows.

The **closed-circuit helium dilution** test requires the patient to rebreathe from a spirometer that contains a known volume of gas (V_1) and a known concentration (C_1) of helium (He), usually 10 percent. The patient is "switched-in" to the closed-circuit system at the end of a normal tidal volume breath

FIGURE 3-2 How obstructive lung disorders alter lung volumes and capacities. IRV = inspiratory reserve volume; V_T = tidal volume; ERV = expiratory reserve volume; RV = residual volume; VC = tidal capacity; IC = inspiratory capacity; FRC = functional residual capacity; TLC = total lung capacity.

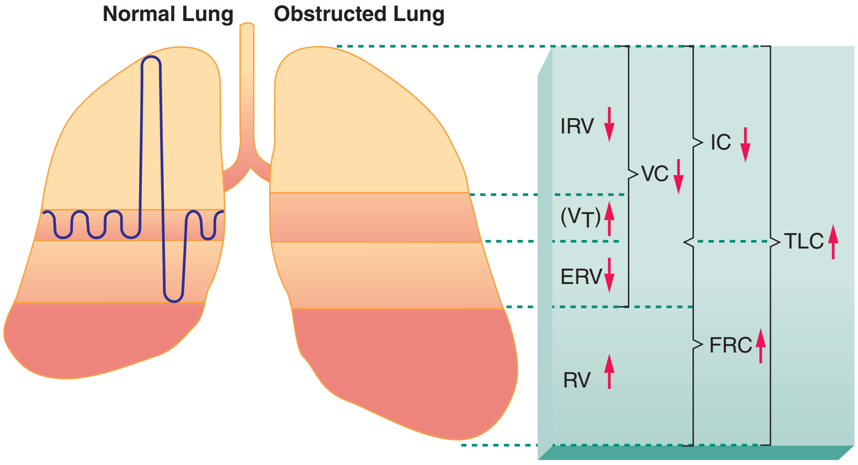
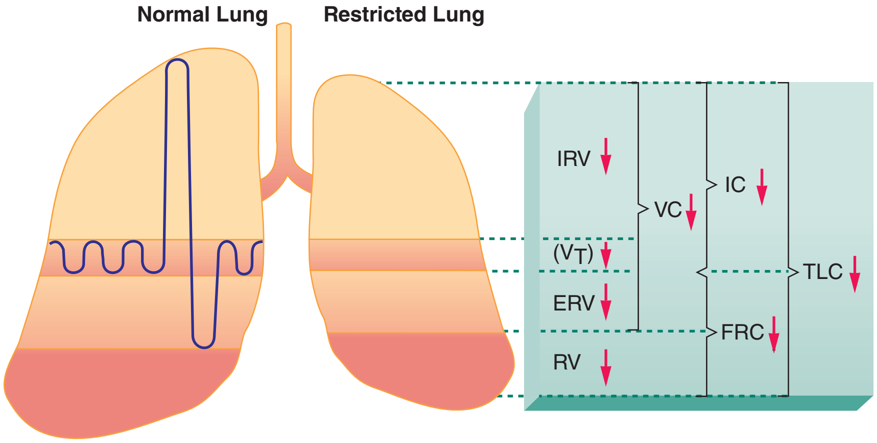


FIGURE 3-3 How restrictive lung disorders alter lung volumes and capacities. IRV = inspiratory reserve volume; V_T = tidal volume; ERV = expiratory reserve volume; RV = residual volume; VC = vital capacity; IC = inspiratory capacity; FRC = functional residual capacity; TLC = total lung capacity.



Clinical Connection 3-1

Obstructive Lung Disorders

An obstructive lung disorder is characterized by a variety of abnormal conditions of the tracheobronchial tree—such as bronchial secretions, mucus plugging, bronchospasm, and distal airway weakening—that cause a reduction of gas flow out of the lungs and air trapping. The flow of gas is especially reduced during a forced exhalation. The FEV_1/FVC ratio is the best indicator of an obstructive lung disorder. There are only a few obstructive lung disorders—**cystic fibrosis, bronchitis, asthma, bronchiectasis,** and **emphysema**. These can be remembered by the acronym CBABE, which is the first letter of each condition. The respiratory therapist will often treat patients with these diseases. When chronic bronchitis and emphysema appear together as one disease complex, the patient is said to have **chronic obstructive pulmonary disease (COPD)**.

Clinical Connection 3-2

Restrictive Lung Disorders

A restrictive lung disorder is characterized by any pathologic condition that causes a restriction of the lungs or chest wall—which, in turn, causes a decrease in lung volumes and capacities. Common restrictive lung disorders treated by the respiratory therapist include pneumonia, pulmonary edema, flail chest, pneumothorax, pleural effusion, chronic interstitial lung disease, lung cancer, acute respiratory distress syndrome, and alveolar collapse (atelectasis).

(i.e., the level at which only the FRC is left in the lungs). A helium analyzer continuously monitors the He concentration. Exhaled carbon dioxide is chemically removed from the system. The gas in the patient's FRC, which initially contains no He, mixes with the gas in the spirometer. This dilutes the He throughout the entire system (i.e., patient's lungs, spirometer, and circuit). The test lasts for about 7 minutes.

When the He changes by less than 0.2 percent over a period of 1 second, the test is terminated. The He concentration at this point is C_2. The final volume of the entire system—the He circuit and lungs (V_2)—can be calculated by using the following formula:

$$V_1C_1 = V_2C_2$$

which is rearranged to solve for V_2 as follows:

$$V_2 = \frac{V_1C_1}{C_2}$$

The FRC can then be calculated by subtracting the initial spirometer volume (V_1) from the equilibrium volume (V_2). (FRC $= V_2 - V_1$). The RV is determined by FRC − ERV. The TLC can be calculated by RV + VC.

In the **open-circuit nitrogen washout** test, the patient breathes 100 percent oxygen through a one-way valve for up to 7 minutes. The patient is "switched-in" to the system at the end of a normal tidal volume (i.e., the level at which only the FRC is left in the lungs). At the beginning of the test, the nitrogen (N_2) concentration in the alveoli is 79 percent (C_1). During each breath, oxygen is inhaled and N_2-rich gas from the FRC is exhaled. Over several minutes, the N_2 in the patient's FRC is effectively washed out. In patients with normal lungs, this occurs in 3 minutes or less. Patients with obstructive lung disease may not wash out completely even after 7 minutes.

During the washout period, the exhaled gas volume is measured and the average concentration of N_2 is determined with a nitrogen analyzer. The test is complete when the N_2 concentration drops from 79 to 1.5 percent or less. The FRC (V_1) can then be determined by taking the initial concentration of N_2 in the FRC gas (C_1), the total volume of gas exhaled during the washout period (V_2), and the average concentration of N_2 in the exhaled gas (C_2) and inserting the findings into the following equation:

$$V_1 = \frac{C_2V_2}{C_1}$$

The FRC can then be calculated by subtracting the known volume of the breathing circuit (V_{bc}) and correcting for the volume of N_2 excreted into the lungs from the plasma and body tissues during the test (V_{tis}):

$$\text{FRC} = V_1 - V_{bc} + V_{tis}$$

Body plethysmography measures the gas volume within the lungs (thoracic gas volume [V_{TG}]) indirectly by using a modification of Boyle's law. During the test, the patient sits in an airtight chamber called a *body box*. Initially, the patient is permitted to breathe quietly through an open valve (shutter). Once the patient is relaxed, the test begins at the precise moment the patient exhales to the end tidal volume level (FRC). At this point, the shutter is closed and the patient is instructed to pant against the closed shutter. Pressure and volume changes are monitored during this period. The alveolar pressure changes caused by the compression and decompression of the lungs are estimated at the mouth. Because there is no airflow during this period, and because the temperature is kept constant, the pressure and volume changes can be used to determine the trapped volume (FRC) by applying Boyle's law. This method is generally considered to be the most accurate of the three methods for measuring RV.

Pulmonary Mechanics

In addition to measuring volumes and capacities, the rate at which gas flows in and out of the lungs can also be measured. Expiratory flow rate measurements provide data on the integrity of the airways and the severity of airway impairment, as well as indicating whether the patient has a large airway or a small airway problem. Collectively, the tests for measuring expiratory flow rates are referred to as the pulmonary mechanic measurements.

Pulmonary Mechanic Measurements

Forced Vital Capacity (FVC)

The FVC is the maximum volume of gas that can be exhaled as forcefully and rapidly as possible after a maximal inspiration (Figure 3–4). The FVC is the most commonly performed pulmonary function measurement. In the normal individual, the *total expiratory time* (TET) required to completely exhale the FVC is 4 to 6 seconds. In obstructive lung disease (e.g., chronic bronchitis), the TET increases. TETs greater than 10 seconds have been reported in these patients.

In the normal individual, the FVC and the slow vital capacity (SVC) are usually equal. In the patient with obstructive lung disease, the SVC is often normal and the FVC is usually decreased because of air trapping. The FVC is also decreased in restrictive lung disorders (e.g., pulmonary fibrosis, adult respiratory distress syndrome, pulmonary edema). This is primarily due to the low vital capacity associated with restrictive disorders. The TET needed to exhale the FVC in a restrictive disorder, however, is usually normal or even lower than normal because the elasticity of the lung is high (low compliance) in restrictive disorders.

Forced Expiratory Volume Timed (FEV_T)

The FEV_T is the maximum volume of gas that can be exhaled within a specific time period. This measurement is obtained from an FVC. The most frequently used time period is 1 second. Other commonly used periods are 0.5, 2, and 3 seconds (Figure 3–5). Normally, the percentage of the total FVC exhaled during these time periods is as follows: $FEV_{0.5}$, 60 percent; FEV_1, 83 percent; FEV_2, 94 percent; and FEV_3, 97 percent. Patients with *obstructive pulmonary disease* have a decreased FEV_T. Patients with *restrictive lung disease* also have a decreased FEV_T, primarily due to the low vital capacity associated with such disease. The FEV_T decreases with age.

Forced Expiratory Volume$_{1\ Sec}$/Forced Vital Capacity Ratio (FEV_1/FVC Ratio)

The *FEV_1/FVC ratio* is the comparison of the amount of air exhaled in 1 second to the total amount exhaled during an FVC maneuver. Because the FEV_1/FVC ratio is expressed as a percentage, it is commonly referred to as *a forced expiratory volume in 1 second percentage* ($FEV_{1\%}$). As mentioned previously, the normal adult exhales 83 percent or more of the FVC in 1 second (FEV_1). Thus, under normal conditions the patient's $FEV_{1\%}$

FIGURE 3-4 Forced vital capacity (FVC). A = point of maximal inspiration and the starting point of an FVC.

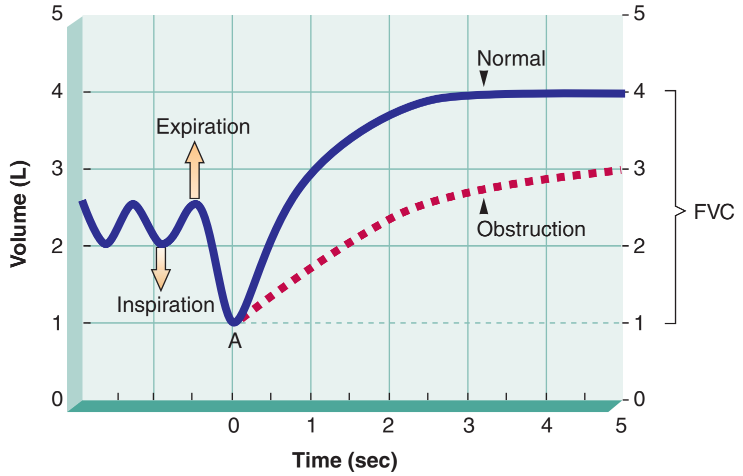
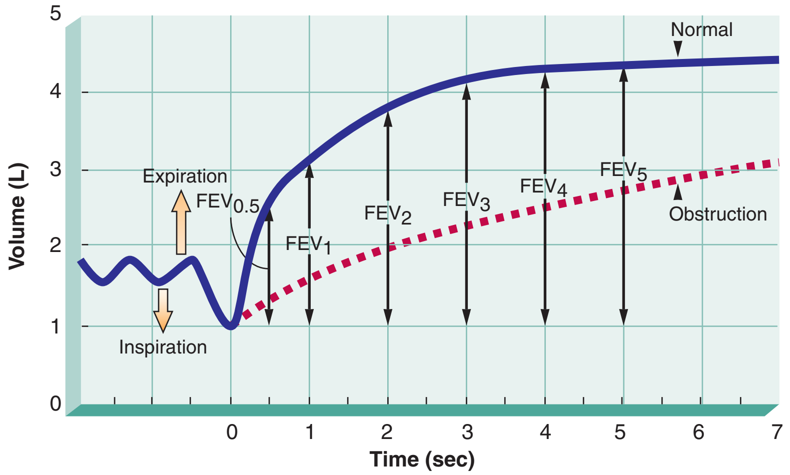


FIGURE 3-5 Forced expiratory volume timed (FEV_T).



should also be 83 percent or greater. Clinically, however, an $FEV_{1\%}$ of 65 percent or more is often used as an acceptable value in older patients.

Key Pulmonary Function Measurements Used to Differentiate between an Obstructive or Restrictive Pulmonary Disorder

Collectively, the **FVC**, **FEV_1**, and the **FEV_1/FEV ratio**—(commonly called the **$FEV_{1\%}$**) are the three most commonly used pulmonary function measurements to (1) differentiate between an obstructive and restrictive lung disorder and (2) determine the severity of a patient's pulmonary disorder. For different reasons, the FVC and FEV_1 are both reduced in obstructive and restrictive lung disorders.

In a restrictive lung disorder, the patient can only inhale smaller volumes of air. As a result, only smaller volumes of air can be exhaled—a smaller FVC and FEV_1. In an obstructive lung disorder, the FEV_1 is

Clinical Connection 3-3

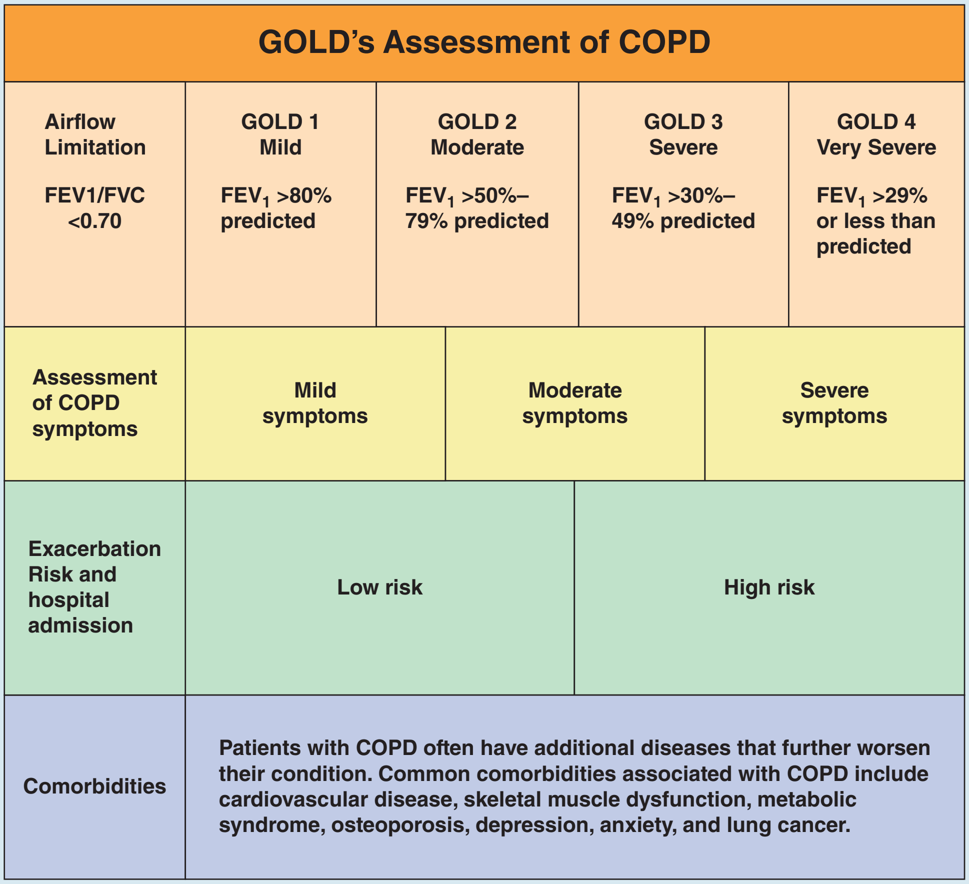
The FEV_1 /FVC Ratio and FEV_1 in the Assessment and Management of Chronic Obstructive Pulmonary Disease (COPD)

The Global Initiative for Chronic Obstructive Lung Disease (GOLD) provides an excellent framework using the FEV_1/FVC ratio (commonly written as $FEV_{1\%}$) and FEV_1 values to categorize the airflow limitation of a patient with COPD as **GOLD I** (mild), **GOLD II** (moderate), **GOLD III** (severe), or **GOLDS IV** (very severe). According to GOLD, before an effective treatment plan for COPD can be outlined, a thorough COPD assessment must first be performed. The primary goals of COPD assessment are to (1) establish the degree of airflow limitation, (2) determine the impact of the COPD the symptoms on the patient's health status, and (3) ascertain the risk of future events (e.g., exacerbations or hospital admissions). As summarized in Figure 3-6, to achieve this goal, GOLD recommends the assessment of the following features of the disease independently: airflow limitation, COPD symptoms, exacerbation risk, and comorbidities.

(*Continued*)

Clinical Connection 3-3, Continued

FIGURE 3-6 The Global Initiative for Chronic Obstructive Lung Disease (GOLD) provides an excellent framework to evaluate the severity of COPD.



<table>
<tr><th colspan="13">GOLD's Assessment of COPD</th></tr>
<tr><td>Airflow Limitation
FEV1/FVC <0.70</td><td colspan="3">GOLD 1
Mild
FEV$_1$ >80% predicted</td><td colspan="3">GOLD 2
Moderate
FEV$_1$ >50%–79% predicted</td><td colspan="3">GOLD 3
Severe
FEV$_1$ >30%–49% predicted</td><td colspan="3">GOLD 4
Very Severe
FEV$_1$ >29% or less than predicted</td></tr>
<tr><td>Assessment of COPD symptoms</td><td colspan="4">Mild symptoms</td><td colspan="4">Moderate symptoms</td><td colspan="4">Severe symptoms</td></tr>
<tr><td>Exacerbation Risk and hospital admission</td><td colspan="6">Low risk</td><td colspan="6">High risk</td></tr>
<tr><td>Comorbidities</td><td colspan="12">Patients with COPD often have additional diseases that further worsen their condition. Common comorbidities associated with COPD include cardiovascular disease, skeletal muscle dysfunction, metabolic syndrome, osteoporosis, depression, anxiety, and lung cancer.</td></tr>
</table>

reduced because of the increased airway resistance. The FVC is reduced because of early airway closure and air trapping. In other words, the trapped air is blocked from being available for the FVC measurement.

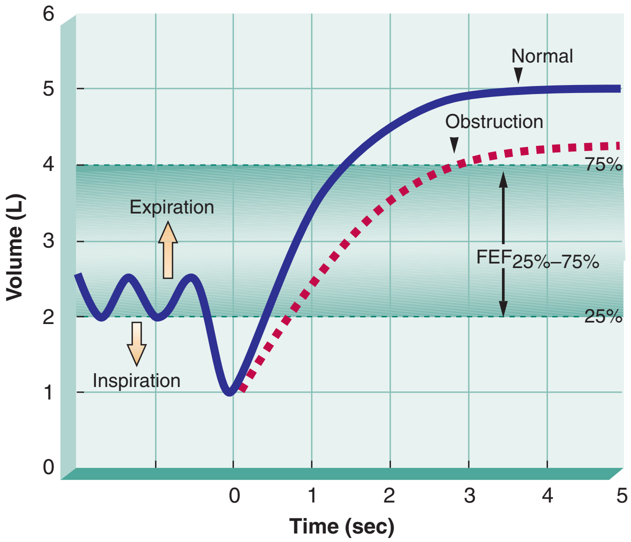
The FEV$_{1\%}$ serves as the key pulmonary function measurement to differentiate between an obstructive and restrictive lung disorder. In other words, the comparison of the FEV$_1$ with the FVC—the FEV$_1$/FEV ratio—provides a clear distinction between these two pulmonary disorders as follows:

- In an **obstructive lung disorder**, the FEV$_{1\%}$ is *decreased.* As discussed earlier, a normal FEV$_{1\%}$ is 83 percent or greater. Only a patient with an obstructive disorder will exhale less than 70 percent of their FVC in the first second.
- In a **restrictive lung disorder**, the FEV$_{1\%}$ is normal or *increased.*

Forced Expiratory Flow$_{25\%–75\%}$ (FEF$_{25\%–75\%}$)

The FEF$_{25\%–75\%}$ is the average flow rate that occurs during the middle 50 percent of an FVC measurement (Figure 3–7). This average measurement reflects the condition of *medium- to small-sized airways.* The average FEF$_{25\%–75\%}$ for normal healthy men aged 20 to 30 years is about 4.5 L/sec (270 L/min), and

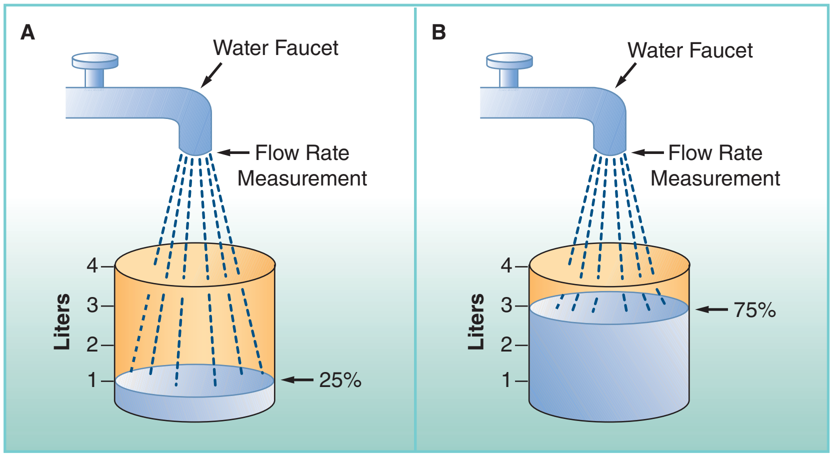
FIGURE 3-7 Forced expiratory flow$_{25\%-75\%}$ (FEF$_{25\%-75\%}$)



for women of the same age, about 3.5 L/sec (210 L/min). The FEF$_{25\%-75\%}$ decreases with age and in obstructive lung disease. In obstructive lung disease, flow rates as low as 0.3 L/sec (18 L/min) have been reported.

The FEF$_{25\%-75\%}$ is also decreased in patients with restrictive lung disorders, primarily because of the low vital capacity associated with restrictive lung disorders. Although the FEF$_{25\%-75\%}$ has no value in distinguishing between obstructive and restrictive disease, it is helpful in further confirming—or ruling out—an obstructive pulmonary disease in patients with borderline low FEV$_{1\%}$. Conceptually, the FEF$_{25\%-75\%}$ is similar to measuring, and then averaging, the flow rate from a water faucet when 25 and 75 percent of a specific volume of water have accumulated in a measuring container (Figure 3–8).

FIGURE 3-8 The FEF$_{25\%-75\%}$ is similar to measuring and then averaging the flow rate from a faucet when 1 and 3 L of water have accumulated in a 4 L container. **A.** Picture the flow rate from the faucet being measured when 1 L (25 percent) of water has entered a 4 L container **B.** Again, picture the flow rate from the faucet being measured when 3 L (75 percent) of water have entered the 4 L container. Taking the average of the two flow rates would be similar to the FEF$_{25\%-75\%}$, which measures and then averages the flow rate when an individual exhales 25 and 75 percent of the FVC.



Clinical Connection 3-4

Differentiating between Obstructive and Restrictive Lung Disorders

Clinically, the FVC, FEV$_1$, and FEV$_{1\%}$ are commonly used to determine if a patient is suffering from either an obstructive lung disorder or a restrictive lung disorder. For example, a respiratory therapist is called to help care for a 71-year-old male patient who presents in the emergency room short of breath. The patient is using his accessory muscles of inspiration and is pursed-lip breathing. His face appears blue and his blood pressure is 155/95. The patient states that he might have the flu and has been short of breath for the past two days. The patient also states that he had been diagnosed with pneumonia a few years earlier. The patient was asked to perform a bedside spirometry test to help determine if either an restrictive or obstructive lung disorder was present. The patient demonstrates the following pulmonary function values.

PFT Measurement	Predicted	Actual	Percent of Predicted
FVC	4.5 L	3.4 L	75%
FEV$_1$	3.6 L	2.1 L	58%
FEV$_{1\%}$ (FEV$_1$/FVC ratio)	>83%	62%	—

Based on the data provided by this relatively simple bedside spirometry test, an FEV$_{1\%}$ lower than predicted means the patient is demonstrating an obstructive lung problem. Only a patient with an obstructive lung disorder has a reduced FEV$_{1\%}$. When a patient has a restrictive lung problem, the FEV$_{1\%}$ is either normal or increased. To develop a complete therapeutic plan for this patient, a number of clinical procedures will need to be performed, including (1) obtaining a complete patient history, (2) a more comprehensive pulmonary function study, (3) arterial blood gas measurements, and (4) chest X-rays.

Forced Expiratory Flow$_{200–1200}$ (FEF$_{200–1200}$)

The FEF$_{200–1200}$ is the average flow rate that occurs between 200 and 1200 mL of the FVC (Figure 3–9). The first 200 mL of the FVC is usually exhaled more slowly than the average flow rate because of the inertia involved in the respiratory maneuver and the unreliability of response time of the equipment. Because the FEF$_{200–1200}$ measures expiratory flows at high lung volumes, it is a good index of the integrity of *large airway function* (above the bronchioles). Flow rates that originate from the large airways are referred to as the effort-dependent portion of the FVC.[1] Thus, the greater the patient effort, the higher the FEF$_{200–1200}$ value. The average FEF$_{200–1200}$ for healthy men ages 20 to 30 years is about 8 L/sec (480 L/min), and for women of the same age, about 5.5 L/sec (330 L/min).

The FEF$_{200–1200}$ decreases with age and in obstructive lung disease. Flow rates as low as 1 L/sec (60 L/min) have been reported in some patients with obstructive lung disease. The FEF$_{200–1200}$ is also decreased in patients with restrictive lung disorders. This is primarily because of the low vital capacity associated with restrictive lung disorders. Conceptually, the FEF$_{200–1200}$ is similar to measuring, and then averaging, the flow rate from a water faucet when 200 and 1200 mL have accumulated in a measuring container (Figure 3–10).

Peak Expiratory Flow Rate (PEFR)

The peak expiratory flow rate (PEFR) (also known as the *peak flow rate)* is the maximum flow rate that can be achieved during an FVC maneuver (Figure 3–11). The PEFR is most commonly measured at the bedside using a small, handheld flow-sensing device called a **peak flow meter**. Similar to the FEF$_{200–1200}$

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[1] See "The Effort-Dependent Portion of a Forced Expiratory Maneuver" later in this chapter.

FIGURE 3-9 Forced expiratory flow$_{200–1200}$ (FEF$_{200–1200}$).

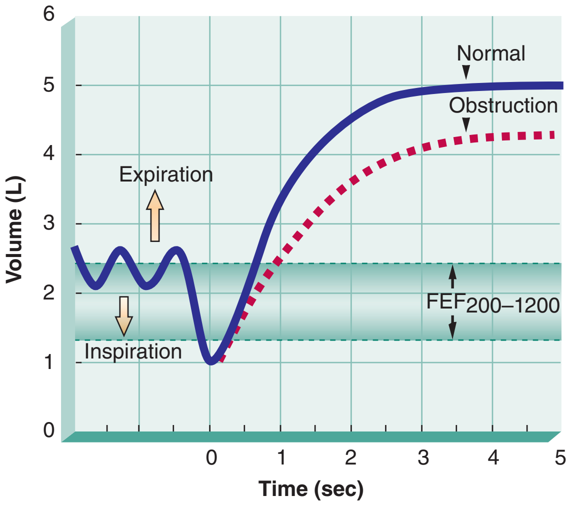
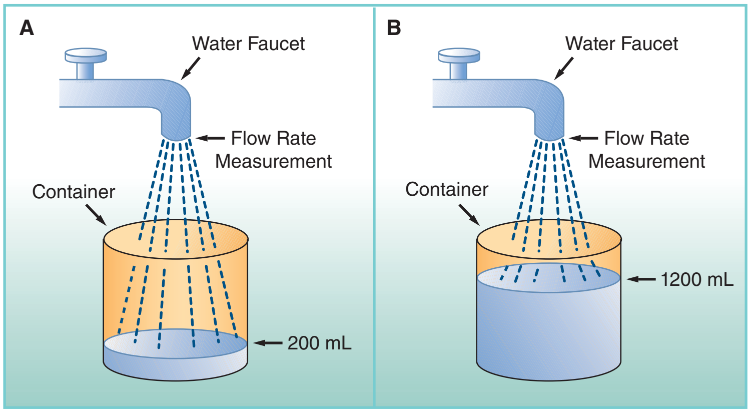


FIGURE 3-10 The FEF$_{200–1200}$ is similar to measuring and then averaging the flow rate of water from a faucet at the precise moment when 200 and 1200 mL of water have accumulated in a container **A.** Picture the flow rate from the faucet being measured when 200 mL of water have entered the container **B.** Then picture the flow rate from the faucet being measured when 1200 mL of water have entered container. Taking the average of the two flow rates would be similar to the FEF$_{200–1200}$, which measures and then averages the flow rate at the precise point when 200 and 1200 mL of gas have been exhaled during an FVC maneuver.



measurement, the PEFR reflects initial flows originating from the large airways during the first part of an FVC maneuver (the effort-dependent portion of the FVC).[2] Thus, the greater the patient effort, the higher the PEFR value.

The average PEFR for normal healthy men ages 20 to 30 years is about 10 L/sec (600 L/min), and for women of the same age, about 7.5 L/sec (450 L/min). The PEFR decreases with age and in obstructive lung disease. The PEFR is an inexpensive and effective bedside measurement that is used both in the hospital and home care setting to evaluate gross changes in airway function and to assess the patient's response to bronchodilator therapy.

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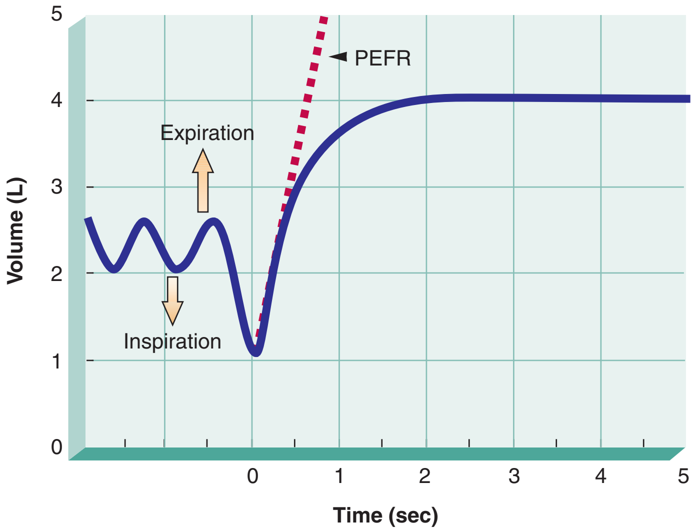
[2] "The Effort-Dependent Portion of a Forced Expiratory Maneuver" later in this chapter.

FIGURE 3-11 Peak expiratory flow rate (PEFR).



Clinical Connection 3-5

Asthma Action Plan—The Green, Yellow, and Red Zones

It is often recommended in children who have asthma that an **asthma action plan** be developed between the parents and the child's doctor. A patient is given a peak flow meter and taught to perform the measurement. Over the course of days and weeks, the patient records his or her personal best peak flow. An asthma action plan is a guide to help monitor the asthma and determine what to do in response to specific symptoms. A common asthma action plan is divided into three zones—green, yellow, and red—similar to the colors on a traffic light. The green zone is 80 percent or better of the personal best peak flow. This is where you want a child to be on a daily basis. The yellow zone is a peak flow that falls between 80 percent and 50 percent of the personal best peak flow. The yellow zone is a warning that the asthma is getting worse and action is needed to prevent an asthmatic attack. The red zone—or less than 50 percent of the patient's personal best peak flow—means the patient is in immediate danger and emergency action must be taken right away! Figure 3–12 provides an overview of the green, yellow, and red asthma action plan.

Note that the peak flow meter used in the asthma action plan is a very important—and very easy to use—diagnostic tool to help monitor a patient with moderate or severe asthma. When patients know their personal best peak flow number,[3] they can actually identify when an asthmatic episode is getting worse—oftentimes, even before they feel any symptoms. The doctor uses the personal best peak flow rate to help determine the patient's green, yellow, and red zones. Although the green, yellow, and red action plan zones are most commonly used with children, the monitoring of peak flow rates can be very beneficial for all asthma patients in all age groups.

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[3] *Peak flow personal best* means the highest peak flow number that can be achieved over a 2- to 3-week period.

Clinical Connection 3-5, Continued

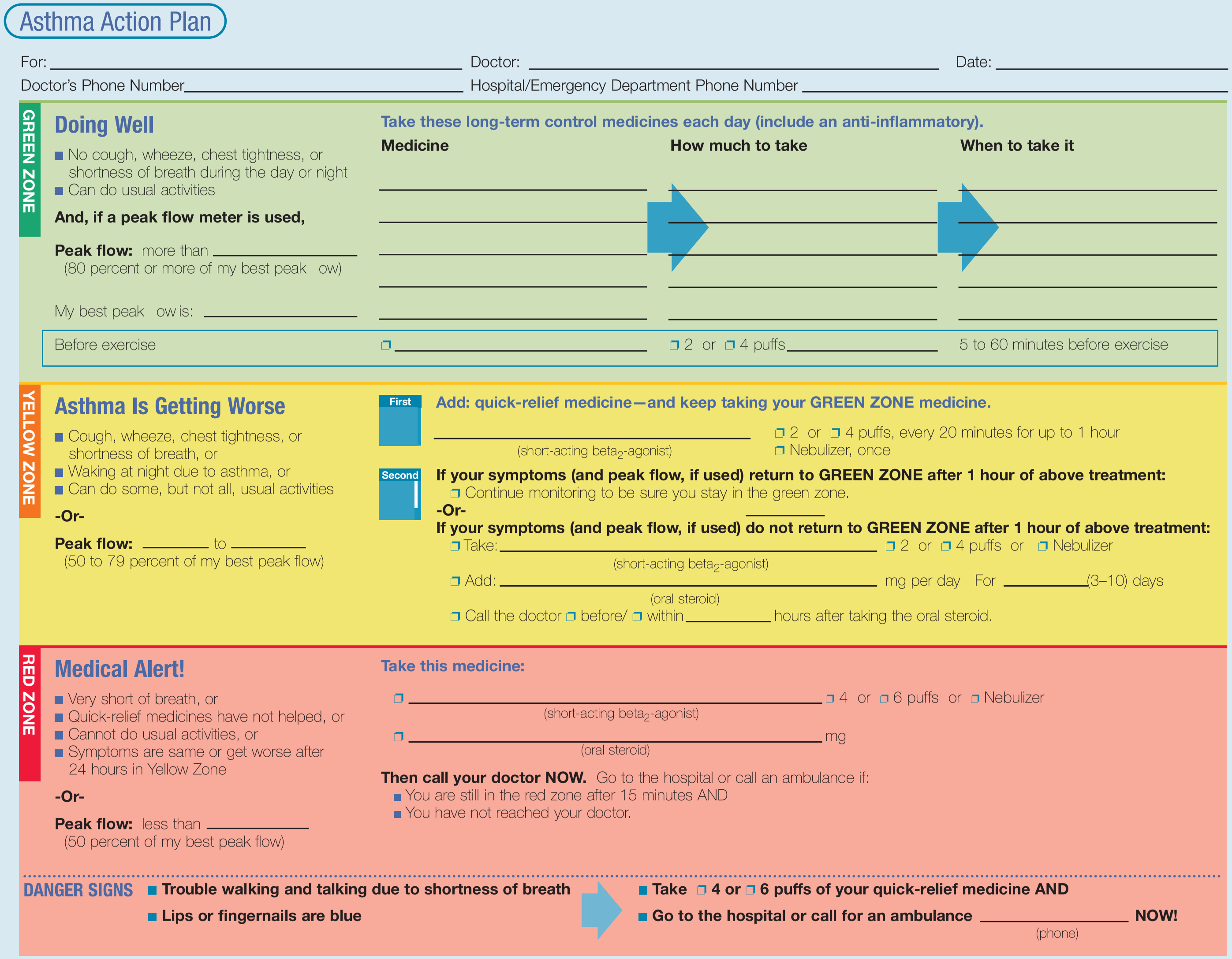


FIGURE 3-12 Asthma action plan: green, yellow, and red zones.

Source: Source: National Heart, Lung, and Blood Institute, National Institute of Health, U.S., www.nhlbi.nih.gov

Asthma Action Plan

For: ____________ Doctor: ____________ Date: ____________

Doctor's Phone Number____________ Hospital/Emergency Department Phone Number ____________

GREEN ZONE

Doing Well

- No cough, wheeze, chest tightness, or shortness of breath during the day or night
- Can do usual activities

And, if a peak flow meter is used,

Peak flow: more than ____________
(80 percent or more of my best peak flow)

My best peak flow is: ____________

Take these long-term control medicines each day (include an anti-inflammatory).

Medicine	How much to take	When to take it
☐ ____________	☐ 2 or ☐ 4 puffs____________	5 to 60 minutes before exercise

Before exercise

YELLOW ZONE

Asthma Is Getting Worse

- Cough, wheeze, chest tightness, or shortness of breath, or
- Waking at night due to asthma, or
- Can do some, but not all, usual activities

-Or-

Peak flow: ____________ to ____________
(50 to 79 percent of my best peak flow)

First **Add: quick-relief medicine—and keep taking your GREEN ZONE medicine.**

____________ (short-acting beta$_2$-agonist) ☐ 2 or ☐ 4 puffs, every 20 minutes for up to 1 hour
☐ Nebulizer, once

Second **If your symptoms (and peak flow, if used) return to GREEN ZONE after 1 hour of above treatment:**

☐ Continue monitoring to be sure you stay in the green zone.

-Or-

If your symptoms (and peak flow, if used) do not return to GREEN ZONE after 1 hour of above treatment:

☐ Take: ____________ (short-acting beta$_2$-agonist) ☐ 2 or ☐ 4 puffs or ☐ Nebulizer

☐ Add: ____________ (oral steroid) mg per day For ____________(3–10) days

☐ Call the doctor ☐ before/ ☐ within____________ hours after taking the oral steroid.

RED ZONE

Medical Alert!

- Very short of breath, or
- Quick-relief medicines have not helped, or
- Cannot do usual activities, or
- Symptoms are same or get worse after 24 hours in Yellow Zone

-Or-

Peak flow: less than ____________
(50 percent of my best peak flow)

Take this medicine:

☐ ____________ (short-acting beta$_2$-agonist) ☐ 4 or ☐ 6 puffs or ☐ Nebulizer

☐ ____________ (oral steroid) mg

Then call your doctor NOW. Go to the hospital or call an ambulance if:

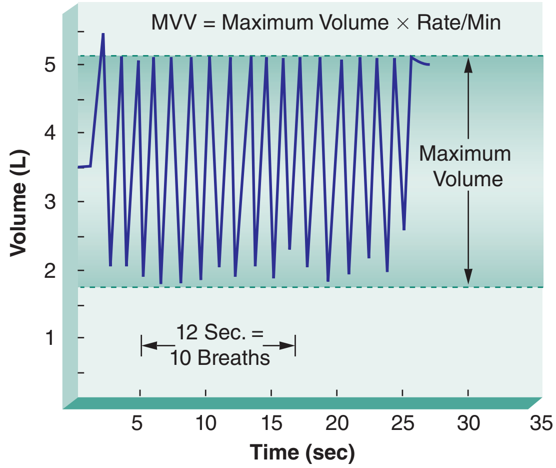
- You are still in the red zone after 15 minutes AND
- You have not reached your doctor.

DANGER SIGNS

- **Trouble walking and talking due to shortness of breath**
- **Lips or fingernails are blue**

- **Take ☐ 4 or ☐ 6 puffs of your quick-relief medicine AND**
- **Go to the hospital or call for an ambulance** ____________ (phone) **NOW!**

FIGURE 3-13 Maximum voluntary ventilation (MVV).



Maximum Voluntary Ventilation (MVV)

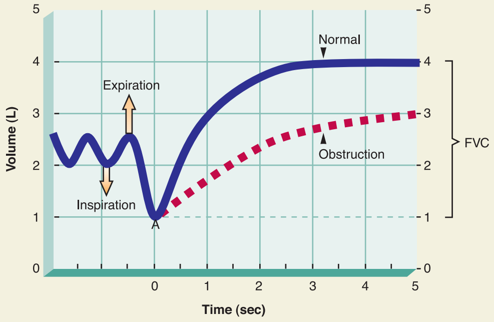
The MVV is the largest volume of gas that can be breathed voluntarily in and out of the lungs in 1 minute (the patient actually performs the test for only 12 seconds—or a minimum of 6 seconds); it is also known as *maximum breathing capacity* (MBC) (Figure 3–13). The MVV is a general test that evaluates the performance of the respiratory muscles' strength, the compliance of the lung and thorax, airway resistance, and neural control mechanisms. The MVV is a broad test and only large reductions are significant. The average MVV for healthy men ages 20 to 30 years is about 170 L/min, and for women of the same age, it is about 110 L/min. The MVV decreases with age and chronic obstructive pulmonary disease. The MVV is relatively normal in restrictive pulmonary disease. The MVV decreases with age.

Table 3–2 provides a summary of the normal forced expiratory flow measurements in the healthy male and female 20 years of age.

Flow-Volume Loop

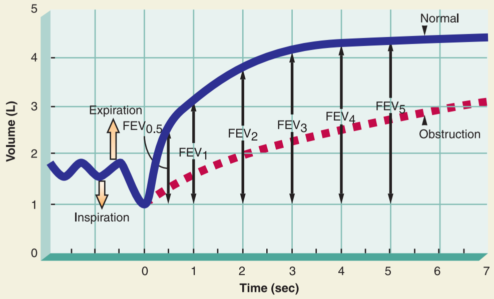
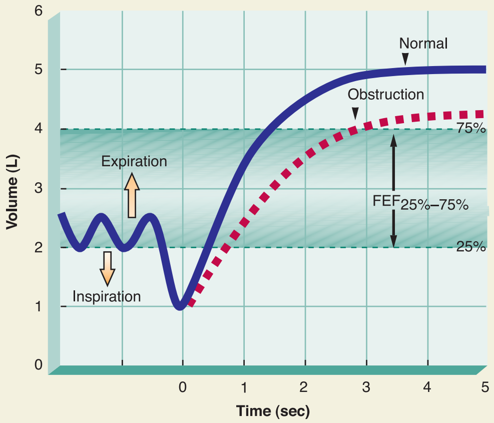
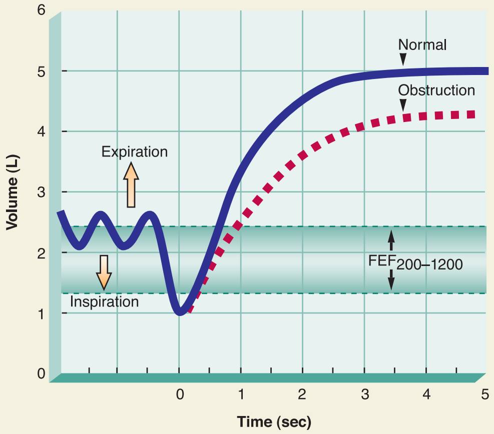
The flow-volume loop is a graphic presentation of a forced vital capacity (FVC) maneuver followed by a forced inspiratory volume (FIV) maneuver. When the FVC and FIV are plotted together, the illustration produced by

TABLE 3-2 Overview of Normal Forced Expiratory Flow Rate Measurements in the Healthy Male and Female 20 to 30 Years of Age

Forced Expiratory Flow Rate Measurement	Description	Male	Female
	**Forced vital capacity (FVC).** *A* is the point of maximal inspiration and the starting point of an FVC. Note the reduction in FVC in obstructive pulmonary disease, caused by dynamic compression of the airways.	Usually equals VC (FVC and VC should be within 150 mL of each other)	Usually equals VC (FVC and VC should be within 150 mL of each other)

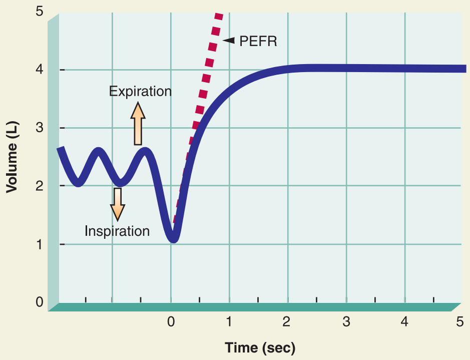
(continued)

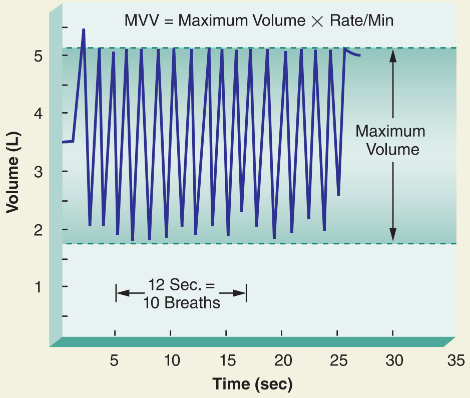
TABLE 3-2 Overview of Normal Forced Expiratory Flow Rate Measurements in the Healthy Male and Female 20 to 30 Years of Age *(continued)*

Forced Expiratory Flow Rate Measurement	Description	Male	Female
	**Forced Expiratory Volume Timed (FEV$_T$).** FEV$_{0.5}$, FEV$_{1.0}$, FEV$_{2.0}$, FEV$_{3.0}$. In obstructive disorders, more time is needed to exhale a specified volume.	FEV$_{0.5}$: 60% FEV$_1$: 83% FEV$_2$: 94% FEV$_3$: 97%	FEV$_{0.5}$: 60% FEV$_1$: 83% FEV$_2$: 94% FEV$_3$: 97%
The FEV$_1$/FVC Ratio can be obtained from the FVC and FEV$_T$ measurements as shown above.	**Forced Expiratory Volume$_{1\ sec}$/Forced Vital Capacity Ratio (FEV$_1$/FVC Ratio).** Commonly called **forced expiratory volume in one second percentage (FEV$_{1\%}$).**	Derived by dividing the predicted FEV$_1$ by the predicted FVC Should be >70%	Derived by dividing the predicted FEV$_1$ by the predicted FVC Should be >70%
	**Forced Expiratory Flow$_{25\%–75\%}$ (FEF$_{25\%–75\%}$).** This test measures the average rate of flow between 25% and 75% of an FVC. The flow rate is measured when 25% of the FVC has been exhaled and again when 75% of the FVC has been exhaled. The average rate of flow is derived by dividing the combined flow rates by 2.	4.5 L/sec (270 L/min)	3.5 L/sec (210 L/min)
	**Forced Expiratory Flow$_{200–1200}$ (FEF$_{200–1200}$).** This test measures the average rate of flow between 200 and 1200 mL of an FVC. The flow rate is measured when 200 mL have been exhaled and again when 1200 mL have been exhaled. The average rate of flow Is derived by dividing the combined flow rates by 2.	8 L/sec (480 L/min)	5.5 L/sec (330 L/min)

(continued)

TABLE 3-2 Overview of Normal Forced Expiratory Flow Rate Measurements in the Healthy Male and Female 20 to 30 Years of Age *(continued)*

<table>
<tr><th>Forced Expiratory Flow Rate Measurement</th><th>Description</th><th>Male</th><th>Female</th></tr>
<tr><td>


</td><td>Peak Expiratory Flow Rate (PEFR). The maximum flow rate (steepest slope of the volume/time trace) generated during an FVC maneuver.</td><td>8-10 L/sec (500–600 L/min)</td><td>7.5 L/sec (450 L/min)</td></tr>
<tr><td>


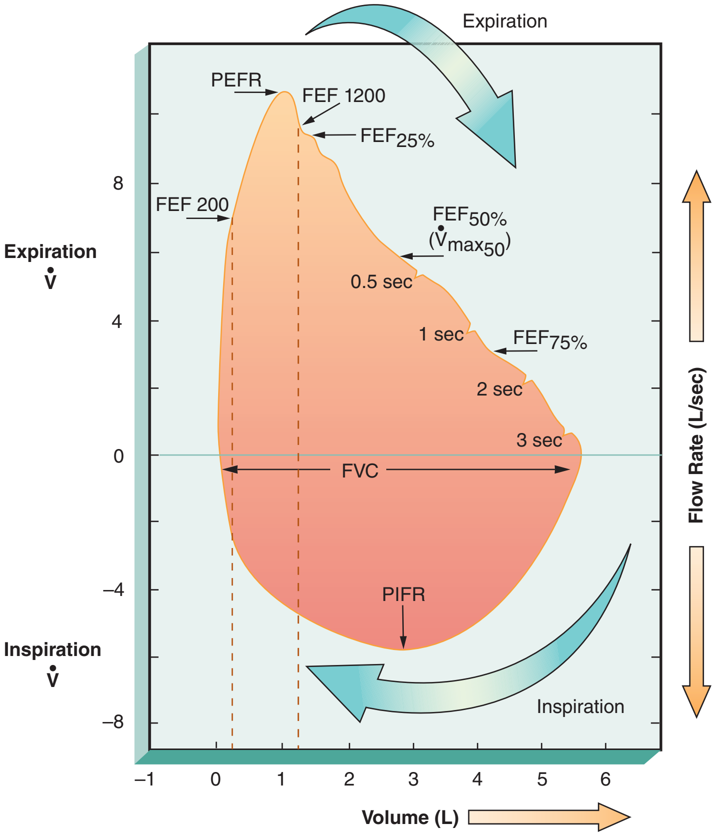
</td><td>Maximum Voluntary Ventilation (MVV). The largest volume of gas that can be breathed voluntarily in and out of the lungs in 1 minute.</td><td>170 L/min</td><td>110 L/min</td></tr>
</table>

the two curves is called a **flow-volume loop** (Figure 3–14). The flow-volume loop compares both the *flow rates* and *volume changes* produced at different points of an FVC and FIV maneuver. Although the flow-volume loop does not measure the FEF$_{200-1200}$ and FEF$_{25\%-75\%}$, it does show the *maximum flows* ($\dot{V}_{max}$) at any point of the FVC. The most commonly reported maximum flows are FEF$_{25\%}$, FEF$_{50\%}$, and FEF$_{75\%}$. In healthy individuals, the FEF$_{50\%}$ (also called the $\dot{V}_{max_{50}}$) is a straight line because the expiratory flow decreases linearly with volume throughout most of the FVC range. In subjects with obstructive lung disease however, the flow rate decreases at low lung volumes, causing the FEF$_{50\%}$ to decrease. This causes a cuplike or scooped out effect on the flow-volume loop.

To summarize, depending on the sophistication of the equipment, several important measurements can be obtained from the flow-volume loop, including the following:

- PEFR
- PIFR
- FVC
- FEVT
- FEV$_1$/FVC ratio (FEV$_{1\%}$)
- FEF$_{25\%}$
- FEF$_{50\%}$ ($\dot{V}_{max_{50}}$)
- FEF$_{75\%}$

FIGURE 3-14 Normal flow-volume loop. PEFR = peak expiration flow rate; PIFR = peak inspiratory flow rate; FVC = forced vital capacity; FEF$_{25\%-75\%}$ = forced expiratory flow$_{25\%-75\%}$; FEF$_{50\%}$ = forced expiratory flow$_{50\%}$ (also called $\dot{V}_{max_{50}}$).



Clinical Connection 3-6

Both an Obstructive and a Restrictive Lung Disorder

In the Clinical Application Case 2 (see page 179), the respiratory therapist is called to help care for a 29-year-old with no previous history of pulmonary disease who enters the hospital system complaining of a frequent cough and shortness of breath. The patient reports that his respiratory distress developed shortly after breathing paint fumes while working in a small and confined area. This case illustrates a patient with both an acute obstructive and a restrictive lung disorder. Because of the excessive secretions caused by the paint fumes and subsequent airway infection, the patient's pulmonary mechanic measurements (e.g., FVC, FEV$_T$, and PEFR) all were decreased. In addition, because of the mucus plugging and subsequent alveolar collapse, the patient's lung volumes and capacities (e.g., RV, FRC, and VC) all decrease. This case further demonstrates how a variety of pulmonary function measurements are used to evaluate and verify the patient's pulmonary status. Note: This clinical case example is of a patient with an acute obstructive and acute restrictive lung disorder. With appropriate treatment, acute pulmonary problems often resolve without long-term lung injury. Chronic obstructive and chronic restrictive lung conditions will not resolve.

Flow-volume loop measurements graphically illustrate both obstructive (Figure 3–15) and restrictive lung problems (Figure 3–16). Table 3–3 summarizes the average dynamic flow rate values found in healthy men and women ages 20 to 30 years.

Factors Affecting Predicted Normal Values

A number of factors affect the normal predicted lung volumes and capacities, including height, weight, age, gender, and race. Among individuals of the same gender, **height** is the most important factor that affects pulmonary function. Taller subjects have greater pulmonary function values—especially in terms of lung volumes, lung capacities, and diffusion capacity values. An individual's height is not as significant in expiratory flow rate measurements (e.g., FVC, FEV_1, or PEFR). In children, normal pulmonary function values are more directly related to height than age, up until the child is about 60 inches (152 cm) tall. After a child reaches this height, the age of the patient begins to be a factor in predicting normal values.

A patient's **weight** is sometimes taken into account along with height. The effect of weight on a patient's lung volumes can be seen when comparing adult subjects of the same height—especially in the obese patient. In general, as weight increases beyond a patient's normal, lung volumes decrease. A patient's **age** can affect a patient's normal lung volumes and capacity values. After the age of 25, lung volumes, expiratory flow rates, and diffusing capacity values tend to decrease.

The **gender** of the patient affects the predicted normal pulmonary function values. Male subjects typically generate greater predicted lung volumes, expiratory flow rates, and diffusing capacities than female subjects of the same age and height. Finally, a patient's race or ethnic origin has been shown to have some effect on normal predicted values. Black, Hispanic, and Asian patients typically have smaller predicted pulmonary function values than subjects of European-descent origin.

FIGURE 3-15 Flow-volume loop, obstructive pattern. FVC = forced vital capacity.

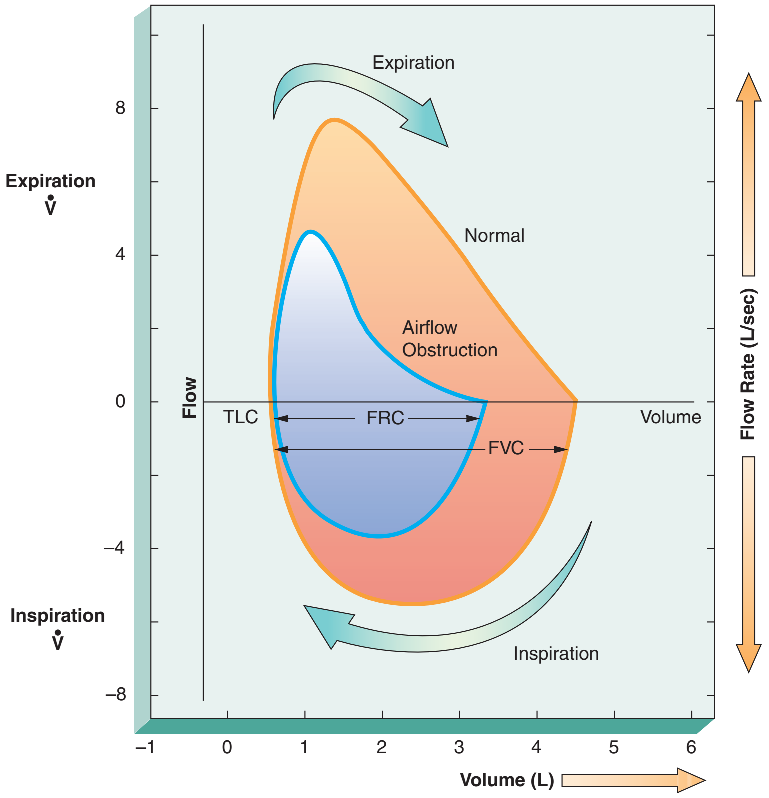


FIGURE 3-16 Flow-volume loop, restrictive pattern. FVC = forced vital capacity.

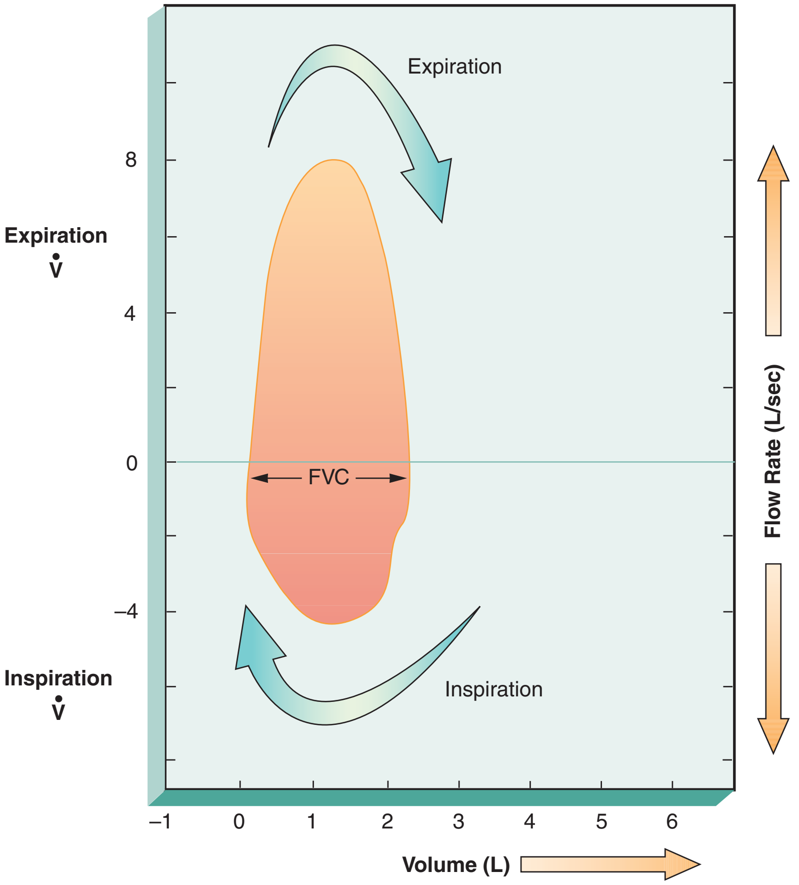


TABLE 3-3 **Average Dynamic Flow Rate Measurements in Healthy Men and Women 20 to 30 Years of Age**

Measurement*	Men	Women
FEV_t		
$FEV_{0.5}$	60%	60%
$FEV_{1.0}$	83%	83%
$FEV_{2.0}$	94%	94%
$FEV_{3.0}$	97%	97%
$FEF_{200-1200}$	8 L/sec (480 L/min)	5.5 L/sec (330 L/min)
$FEF_{25\%-75\%}$	4.5 L/sec (270 L/min)	3.5 L/sec (210 L/min)
PEFR	10 L/sec (600 L/min)	7.5 L/sec (450 L/min)
MVV	170 L/min	110 L/min

* See text for explanation of abbreviations.

How the Effects of Dynamic Compression Decrease Expiratory Flow Rates

The Effort-Dependent Portion of a Forced Expiratory Maneuver

During approximately the first 30 percent of an FVC maneuver, the maximum peak flow rate is dependent on the amount of muscular effort exerted by the individual. This portion of the FVC maneuver originates from the large airways and is referred to as **effort dependent**. As discussed earlier, the $FEF_{200-1200}$ and PEFR measurements reflect flow rates from the large airways. Thus, the greater the patient effort, the higher the $FEF_{200-1200}$ and PEFR values.

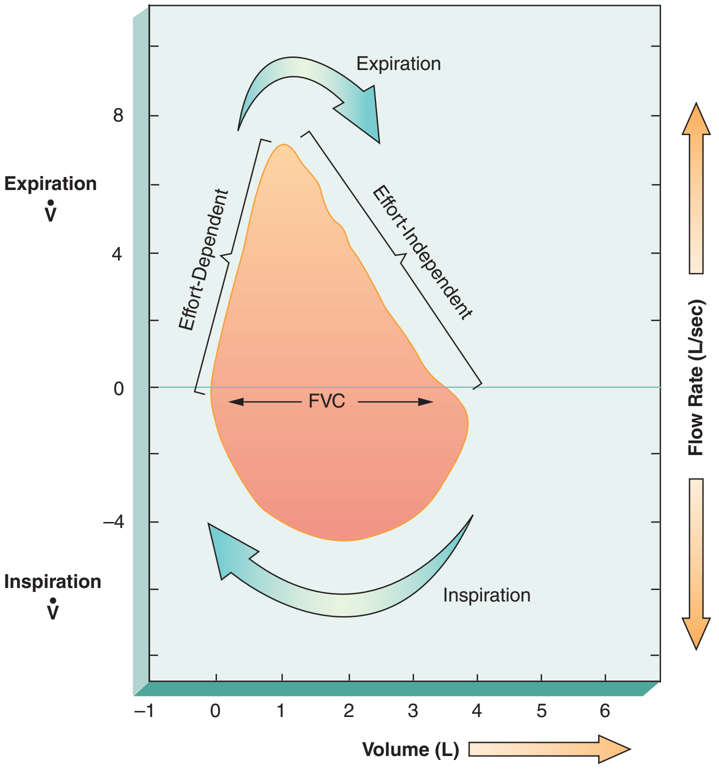
The Effort-Independent Portion of a Forced Expiratory Maneuver

The flow rate during approximately the last 70 percent of an FVC maneuver is **effort independent**. That is, once a maximum flow rate has been attained, the flow rate cannot be increased by further muscular effort.

The lung volume at which the patient initiates a forced expiratory maneuver also influences the maximum flow rate. As lung volumes decline, flow also declines. The reduced flow, however, is the maximum flow for that particular volume.

Figure 3–17 illustrates where the effort-dependent and effort-independent portions of a forced expiratory maneuver appear on a flow-volume loop.

FIGURE 3-17 The effort-dependent and effort-independent portions of a forced expiratory maneuver in a flow-volume loop measurement. FVC = forced vital capacity.



Dynamic Compression of the Bronchial Airways

The limitation of the flow rate that occurs during the last 70 percent of an FVC maneuver is due to the **dynamic compression** of the walls of the airways. As gas flows through the airways from the alveoli to the atmosphere during passive expiration, the pressure within the airways diminishes to zero (Figure 3–18A).

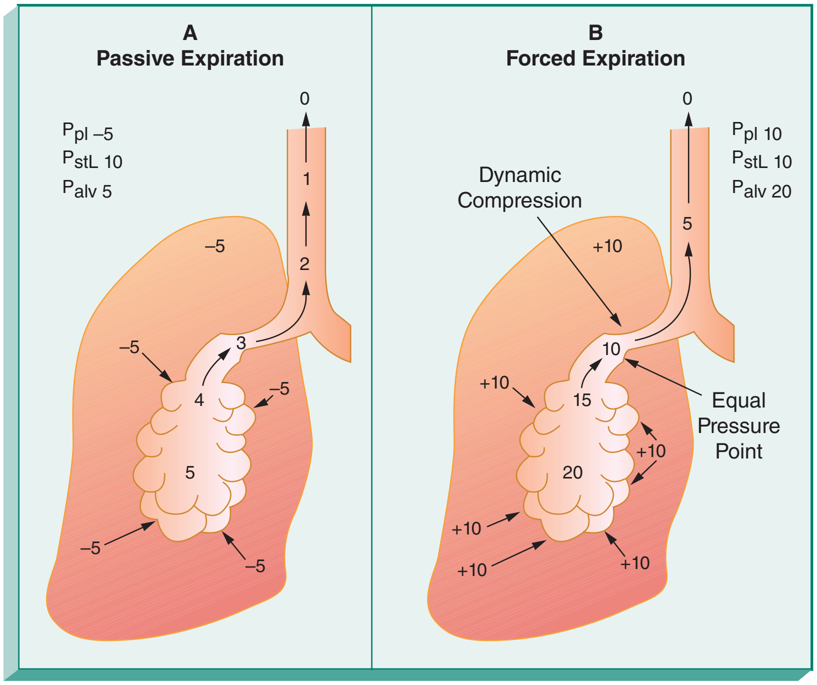
During a forced expiratory maneuver, however, as the airway pressure decreases from the alveoli to the atmosphere, there is a point at which the pressure within the lumen of the airways equals the pleural pressure surrounding the airways. This point is called the **equal pressure point**.

Downstream (i.e., toward the mouth) from the equal pressure point, the lateral pressure within the airway becomes less than the surrounding pleural pressure. Consequently, the airways are compressed. As muscular effort and pleural pressure increase during a forced expiratory maneuver, the equal pressure point moves upstream (i.e., toward the alveolus). Ultimately, the equal pressure point becomes fixed where the individual's flow rate has achieved maximum (Figure 3–18B). In essence, once dynamic compression occurs during a forced expiratory maneuver, increased muscular effort merely augments airway compression, which, in turn, increases airway resistance.

As the structural changes associated with certain respiratory diseases (e.g., COPD) intensify, the patient commonly responds by increasing intrapleural pressure during expiration to overcome the increased airway resistance produced by the disease. By increasing intrapleural pressure during expiration, however, the patient activates the dynamic compression mechanism, which in turn further reduces the diameter of the bronchial airways. This results in an even greater increase in airway resistance.

FIGURE 3-18

The dynamic compression mechanism. **A.** During passive expiration, static elastic recoil pressure of the lungs (P_{stL}) is 10, pleural pressure (P_{p1}) at the beginning of expiration is −5, and alveolar pressure (P_{a1v}) is +5. In order for gas to move from the alveolus to the atmosphere during expiration, the pressure must decrease progressively in the airways from +5 to 0. As A shows, P_{pl} is always less than the airway pressure. **B.** During forced expiration, P_{pl} becomes positive (+10 in this illustration). When this P_{pl} is added to the P_{stL} of +10, P_{alv} becomes +20. As the pressure progressively decreases during forced expiration, there must be a point at which the pressures inside and outside the airway wall are equal. This point is the equal pressure point. Airway compression occurs downstream (toward the mouth) from this point because the lateral pressure is less than the surrounding wall pressure.



Clinical Connection 3-7

Spirometry Confirmation of Dynamic Compression

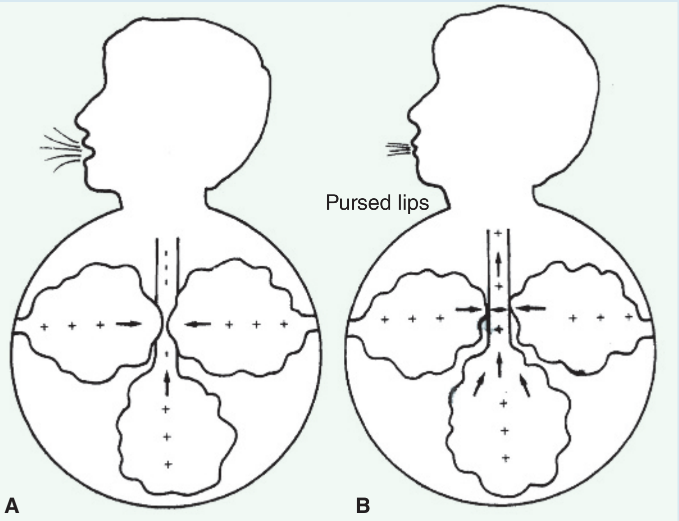
In the Clinical Application Case 1 (see page 177), the respiratory therapist is called to help care for a 16-year-old girl with a long history of asthma who became short of breath while playing volleyball during her high school gym class. The case demonstrates how the measurement of a patient's pulmonary mechanics can serve as an important clinical monitor (e.g., FVC, FEV_1, and PEFR) and the effects of the effort-independent portion of an FVC, dynamic compression, and the equal pressure point. This case further shows that even when the patient makes a strong muscular effort on a FVC test, the closure of her airways—caused by equal pressure point changes and dynamic compression—moves closer to her alveoli. This action, in turn, further increases airway resistance and offsets any improvement in the FVC.

Clinical Connection 3-8

Pursed-Lip Breathing

Pursed-lip breathing is commonly seen in patients suffering from chronic obstructive pulmonary disease (COPD). It is a relatively simple—but effective—technique that many patients learn without formal training. Pursed-lip breathing is characterized by a deep inhalation followed by prolonged expiration through pursed lips—similar to that used for whistling, kissing, or blowing through a flute. Pursed-lip breathing increases the airway pressure during exhalation and, thereby, works to offset the adverse effects of dynamic compression—which, in turn, causes early airway collapse, air trapping, and alveolar overinflation. Pursed-lip breathing creates a natural **continuous positive airway pressure (CPAP)** to hold the airways open from the inside. In addition, pursed-lip breathing has been shown to decrease the patient's breathing rate and yield a ventilatory pattern that is more effective in alveolar gas mixing (Figure 3–19).

FIGURE 3-19 **A.** Schematic illustration of alveoli compression of weakened bronchiole airways during normal expiration in patients with COPD. **B.** The effects of pursed-lip breathing in patients with COPD. The weakened bronchiole airways are kept open by the effects of positive pressure created by pursed lips during expiration.



Courtesy of T. Des Jardins, WindMist LLC

Flow normally is not limited to effort during inspiration. This is because the airways widen as greater inspiratory efforts are generated, thus enhancing gas flow (refer to Figure 2-39).

Diffusion Capacity of Carbon Monoxide (DL_{CO})

The DL_{CO} study measures the amount of carbon monoxide (CO) that moves across the alveolar-capillary membrane. CO has an affinity for hemoglobin that is about 210 times greater than that of oxygen. Thus, in individuals who have normal amounts of hemoglobin and normal ventilatory function, the only limiting factor to the diffusion of CO is the thickness of the alveolar-capillary membrane. In essence, the DL_{CO} study measures the physiologic status of the various anatomic structures that compose the alveolar-capillary membrane.

The CO single-breath technique is commonly used for this measurement. Under normal conditions, the average DL_{CO} value for the resting male is 25 mL/min/mm Hg (standard temperature and pressure, dry [STPD]). This value is slightly lower in females, presumably because of their smaller normal lung volumes. The DL_{CO} may increase threefold in healthy subjects during exercise. The DL_{CO} generally decreases in response to lung disorders that affect the alveolar-capillary membrane. For example, the DL_{CO} is decreased in emphysema because of the alveolar-capillary destruction associated with this lung disease. Other respiratory disorders that decrease a patient's DL_{CO} include chronic interstitial lung disease, pneumonia (alveolar consolidation), pulmonary edema, and acute respiratory distress syndrome.

Maximum Inspiratory and Expiratory Pressure

An individual's **maximum inspiratory pressure (MIP)** and **maximum expiratory pressure (MEP)** are directly related to muscle strength. Table 3–4 shows the average MIP and MEP for the normal, healthy adult. Clinically, the MIP and MEP are used to evaluate the patient's ability to maintain spontaneous, unassisted ventilation. Both the MIP and MEP are commonly measured while the patient inhales and exhales through an endotracheal tube that is attached to a pressure gauge. For the best results, the MIP should be measured at the patient's *residual volume,* and the MEP should be measured at the patient's *total lung capacity*. In general, the patient is ready for a trial of spontaneous or unassisted ventilation when the MIP is greater than −25 cm H_2O (i.e., more negative) and the MEP is greater than 50 cm H_2O.

Rapid Shallow Breathing Index Ratio

The **rapid shallow breathing index (RSBI) ratio** is commonly used to help determine if a mechanically ventilated patient can be successfully weaned off the ventilator. The RSBI is the ratio of the patient's spontaneous breathing rate (breaths/min) to the tidal volume (liters)—also referred to as the frequency to tidal volume (f/V_T) ratio. The RSBI is considered an excellent clinical predictor of weaning success in mechanically ventilated patients. The RSBI is an easy test to perform and, importantly, is independent of the patient's effort and cooperation.

The RSBI measurement is taken 1 minute after disconnecting the spontaneously breathing patient from the ventilator. The discontinuation of ventilator support is likely to be successful when the RSBI is below 105 (normal range, 60 to 105). An RSBI value greater than 105 indicates that the patient will likely fail a weaning trial. For example, if a patient, who is being considered for weaning from mechanical

TABLE 3-4 Maximum Inspiratory and Expiratory Pressures

	MIP	MEP
Male	−125 cm H_2O	230 cm H_2O
Female	−90 cm H_2O	150 cm H_2O

ventilation, demonstrates a spontaneous ventilatory rate of 28 breaths/minute and an average tidal volume of 0.35 L, the patient's RSBI would easily be calculated as follows:

$$\text{RSBI} = 28 \text{ bpm} \div 0.35 \text{ L} = 80$$

Because the patient is clearly below the threshold criteria of 105, and assuming all other weaning criteria are acceptable (e.g., acid-base status, oxygenation status, lung compliance, airway resistance, V_D/V_T, and maximum inspiratory pressure), the patient will likely be successfully weaned off the ventilator.

Clinical Connection 3-9

Ventilator Mechanics Used to Predict Mechanical Ventilation Weaning Success

The respiratory therapist uses a number of the pulmonary function measurements to evaluate the patient's readiness to be successfully weaned off a mechanical ventilator. Common bedside pulmonary function measurements used and the desired criteria are shown in the accompanying table.

Additional pulmonary measurements used to help determine the possible success of weaning a patient off of a mechanical ventilator include (1) acid–base evaluations, (2) oxygenation assessments, and (3) work of breathing measurements (e.g., dynamic and static compliance).

Common Pulmonary Function Measurements Used to Determine Readiness for Weaning and Ventilator Discontinuation

Measurement	Criteria
Spontaneous breathing trial	Tolerates 12–30 min
Respiratory rate (f)	$<$30 breaths/min
Tidal volume (V_T)	$>$5–8 mL/kg
Vital capacity (VC)	$>$10–15 mL/kg
Minute ventilation (V_E)	$<$10–15 L/min
Maximum inspiratory pressure (MIP)	>-25 to -30 cm H_2O in 20 sec
Dead space to tidal volume ratio (VD/V_T)	$<$0.6
Static lung compliance (C_L)	$>$25 mL/cm H_2O
Rapid shallow breathing index (RSBI) ratio (f/V_T)	$<$100 (spontaneous breathing pattern)

Clinical Connection 3-10

The Effects of High and Low Lung and Chest Wall Compliance of Breath-Holding and Breathing

As discussed in Chapter 2, the lung and chest wall are in equal opposition, and it is this interaction of opposing forces that determines the functional reserve capacity (FRC). Total lung and chest wall compliance decrease at both high and low lung volumes because one of the two forces

Clinical Connection 3-10, Continued

(either the lung or chest wall) are moving beyond their normal elastic limits—that is, beyond their normal resting positions.

For example, when an individual fully exhales to his or her residual volume (RV), the "chest wall" quickly reaches its elastic limits. In other words, the compliance of the chest wall decreases—which, in turn, decreases the overall total compliance of the lung–chest wall system (Figure 3-20). On the other hand, when an individual fully inhales to his or her total lung capacity (TLC), the lungs quickly reach their elastic limit. As the lungs approach their full volume capacity, the compliance of the lungs decreases—which, in turn, decreases the overall total compliance of the lung-chest wall system (Figure 3-20).

The reader is challenged to personally experience the effect of lung volume on total lung-compliance by performing the following simple experiment in the lab setting:

1. At resting volume—that is, neither inhaling or exhaling—hold your breath as long as you comfortably can. *Note how comfortable this felt.*
2. Blow out as much air as you can—moving your lung volume to residual volume. You will need to exhale as completely as you possibly can; squeezing out as much air as you are able. When you have exhaled as much as you can, again hold your breath as long as you comfortably can. *Note the comfort level of this breath hold.*
3. Inhale as deeply as you can—moving your lung volume to total lung capacity. You will need to inhale as deeply as you possibly can, filling your lungs to maximum. When you have inhaled as much as you can, again hold your breath as long as you can. *Note comfort level of this breath hold.*

Analysis

Was the breath hold at both residual volume and total lung capacity more uncomfortable than the breath hold at functional reserve volume? As soon as you let go of your breath hold, was your instinct to either inhale or exhale as needed to return to the comfort of your natural resting volume (i.e., FRC)? As you move away from the natural resting volume (FRC), either your lung or chest wall is moving toward its elastic limit, which decreases overall compliance. To maintain any lung volume other than the resting volume of FRC requires muscular work. At FRC, the lung and chest wall are in equal opposition, and this requires no muscular work.

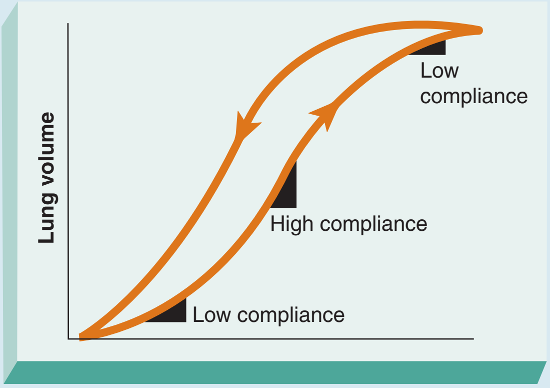
Now try one more related experiment:

1. Inhale close to your TLC. Keeping this increased lung volume, try breathing several regular tidal volume breaths at this increased lung volume level. *Note the comfort level of breathing at this increased "FRC".*
2. Exhale close to your RV. Keeping this decreased lung volume, try breathing several regular tidal volume breaths at this decreased level. *Note the comfort level of breathing at this decreased "FRC."*

Analysis

Was breathing at the higher and lower than normal levels more uncomfortable than breathing from your natural resting state (FRC)? As the lung–chest

FIGURE 3-20 Normal lung/chest wall compliance curve. **A.** Low compliance due to decreased chest wall compliance. **B.** Normal compliance—lungs and chest wall are in balance. **C.** Low compliance due to decreased lung compliance.



(*Continued*)

Clinical Connection 3-10, Continued

wall system moves beyond its natural resting state, compliance decreases. Again, this results in an increase in the work of breathing.

For patients with respiratory disorders that either increase their FRC (e.g., obstructive lung disorders such as asthmatic episodes, emphysema, chronic bronchitis, or cystic fibrosis) or decrease their FRC (e.g., restrictive lung disorders such as pneumonia, adult respiratory distress syndrome, or atelectasis), the work of breathing increases.

To summarize, compliance of the lung–chest wall system decreases at both high and low lung volumes. As the overall compliance of the system decreases, work of breathing subsequently increases. The optimum compliance occurs at the functional reserve volume.

Clinical Connection 3-11

Certified Pulmonary Function Technologist and Registered Pulmonary Function Technologist

The respiratory therapist can further broaden his or her career by pursuing additional education and training as a Certified Pulmonary Function Technologist (CPFT) or a Registered Pulmonary Function Technologist (RPFT). The **National Board for Respiratory Care Inc. (NBRC)** administers the CPFT and RPFT credentialing examinations (www.nbrc.org). Applicants must be 18 years of age or older and satisfy one of the following criteria:

- Have a minimum of an associate degree from a respiratory therapy educational program supported or accredited by the Commission on Accreditation for Respiratory Care (CoARC) or accredited by the Commission on Accreditation of Allied Health Education Programs (CAAHEP).
- Be a Certified Respiratory Therapist (CRT) credentialed by the NBRC.
- Be a Registered Respiratory Therapist (RRT) credentialed by the NBRC.
- Complete 62 semester hours of college credit from a college or university accredited by its regional association or its equivalent, including college-credit-level courses in biology, chemistry, and mathematics. A minimum of 6 months of clinical experience[4] in the field of pulmonary function technology under the direction of a Medical Director of a pulmonary function laboratory or a special care area is also required prior to applying for the examination.
- Be a high school graduate (or the equivalent) and complete two years of clinical experience in the field of pulmonary function technology under the direction of a Medical Director or a pulmonary function laboratory or a special care area prior to applying for the examination.

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[4] Clinical experience is defined as a minimum of 8 hours per week for a calendar year in pulmonary technology under the supervision of a Medical Director of a pulmonary function laboratory or a special care area acceptable to the Board. Clinical experience must be completed before the candidate applies for this examination.

Chapter Summary

The total amount of air that the lungs can accommodate is divided into four separate volumes and four capacities. The lung volumes are the tidal volume (V_T), inspiratory reserve volume (IRV), expiratory reserve volume (ERV), and residual volume (RV). The capacities consist of the vital capacity (VC), inspiratory capacity (IC), functional residual capacity (FRC), and total lung capacity (TLC).

In obstructive lung disorders, the RV, V_T, FRC, and TLC are increased; the VC, IC, IRV, and ERV are decreased. In restrictive lung disorders, the VC, IC, RV, FRC, V_T, and TLC are all decreased. Obstructive lung disorders include chronic bronchitis, emphysema, asthma, cystic fibrosis, and bronchiectasis. Restrictive lung disorders include pneumonia, pulmonary edema, flail chest, pneumothorax, pleural effusion, chronic interstitial lung disease, lung cancer, acute respiratory distress syndrome, and postoperative alveolar collapse.

Because the RV cannot be exhaled, the RV, and lung capacities that contain the RV, is measured indirectly by the closed-circuit helium dilution method, the open-circuit nitrogen washout method, or body plethysmography.

In addition to measuring volumes and capacities, the rate at which gas flows into and out of the lungs can be measured. Collectively, the tests used to measure expiratory flow rates are referred to as pulmonary mechanic measurements. These tests include the forced vital capacity (FVC), forced expiratory volume time (FEV_T), forced expiratory volume 1 sec/forced vital capacity ratio (FEV_1/FVC)—commonly written as $FEV_{1\%}$—forced expiratory flow 25%–75% ($FEF_{25\%–75\%}$), forced expiratory $flow_{200–1200}$ ($FEF_{200–1200}$), peak expiratory flow rate (PEFR), and the maximum voluntary ventilation (MVV).

The flow-volume loop is a graphic presentation of an FVC followed by a forced inspiratory volume (FIV) maneuver. The flow-volume loop compares both the flow rates and volume changes produced at different points of the FVC and FIV maneuver. A number of measurements can be obtained from the flow-volume loop, including the PEFR, PIFR, FVC, FEV_T, FEV/FVC ratio, $FEF_{25\%}$, $FEF_{50\%}$ ($\dot{V}_{max_{50}}$), and $FEF_{75\%}$. The FVC, FEV_1, and the FEV_1/FVC ratio are the most commonly used pulmonary function measurements to (1) evaluate the severity of COPD, (2) help develop a treatment plan, and (3) differentiate between an obstructive and restrictive lung disorder.

To fully understand the pulmonary mechanic measurements, the respiratory therapist must have a basic knowledge of how the effects of dynamic compression decrease expiratory flow rates, including the influences of (1) the effort-dependent portion of a forced expiratory maneuver, (2) the effort-independent portion of a forced expiratory maneuver, and (3) the dynamic compression of the bronchial airways. A clinical connection associated with offsetting the adverse effects of dynamic airway compression is pursed-lip breathing.

Finally, the diffusion capacity of carbon monoxide ($D_{L_{CO}}$) is routinely used to evaluate the physiologic status of the various anatomic structures of the alveolar-capillary membrane. The maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP) are used to directly measure muscle strength to help in predicting mechanical ventilator weaning success. The rapid shallow breathing index (RSBI) ratio is an excellent tool to help in assessing a patient's readiness to be successfully weaned off a ventilator.

Clinical connections associated with the preceding topics include (1) obstructive lung disorders; (2) restrictive lung disorders; (3) the FEV_1/FVC ratio and the FEV_1 in the assessment and management of chronic obstructive pulmonary disease (COPD); (4) differentiating between obstructive and restrictive lung disorders; (5) the asthma action plan—the green, yellow, and red zone; (6) both an obstructive and restrictive lung disorder; (7) spirometry confirmation of dynamic compression; (8) pursed-lip breathing; (9) ventilator mechanics used to predict mechanical ventilation weaning success; (10) the effects of high and low lung compliance on breath-holding; and (11) broadening one's career by pursuing a certified pulmonary function technologist or registered pulmonary function technologist credential.

1 Clinical Application Case

A 16-year-old girl with a long history of asthma became short of breath while playing volleyball during her high school gym class. The head coach took her out of the game and had an assistant coach watch her closely. Even though the patient inhaled a total of four puffs of the bronchodilator albuterol from a metered-dose inhaler over the next 30 minutes, her condition progressively worsened. Concerned, the coach called the patient's mother. Because the patient had had to be given mechanical ventilation on two different occasions, the patient's mother asked the coach to take her daughter directly to the emergency department of the local hospital.

In the emergency department, the patient was observed to be in severe respiratory distress. Her skin was blue and she was using her accessory muscles of

Clinical Application Case 1 (continued)

inspiration. The patient stated, "My asthma is really getting bad." Her vital signs were blood pressure—180/110 mm Hg, heart rate—130 beats/ min, respiratory rate—36 breaths/min, and oral temperature 37°C. While on 4 L/min oxygen via nasal cannula, her hemoglobin oxygen saturation measured by pulse oximetry over the skin of her index finger was 83 percent.

A portable chest X-ray showed that her lungs were hyperinflated and that her diaphragm was depressed (Figure 3–21). Measurement of the patient's forced vital capacity provided the data shown in the accompanying table.

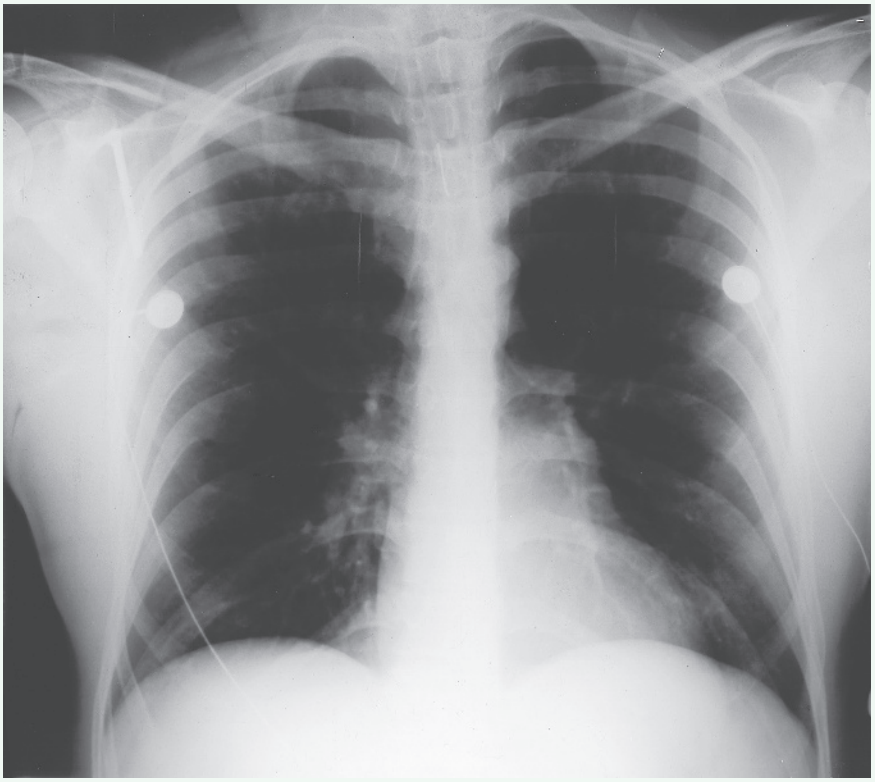
Parameter*	Predicted	Actual
FVC	2800 mL	1220 mL
FEV_1	>83%	44%
PEFR	400 L/min	160 L/min

*FVC = forced vital capacity; FEV_1 = forced expiratory volume in 1 second (see text); PEFR = peak expiratory flow rate.

Because the respiratory therapist felt that the patient did not produce a good effort on her first FVC test, a second test was done. Even though the patient appeared to exhale much more forcefully during the second FVC test, the spirometry results were identical to the previous ones. The patient's mother stated that her daughter's "personal best" peak expiratory flow rate (PEFR) at home was 360 L/min. While the patient was in the emergency department, the nurse started an intravenous infusion. The respiratory therapist increased the patient's oxygen via nasal cannula to 6 L/min. The patient was then given a continuous bronchodilator therapy via a handheld nebulizer per the respiratory care protocol. The medical director of the respiratory care department was notified, and a mechanical ventilator was placed on standby.

One hour later, the patient stated that she was breathing easier. Her skin appeared pink, and she was no longer using her accessory muscles of inspiration. Her vital signs were blood pressure—122/76 mm Hg, heart rate—82 beats/min, and

FIGURE 3-21 X-ray showing presence of asthma.



(Continued)

Clinical Application Case 1 (continued)

respiratory rate—14 breaths/min. On 2 L/min oxygen via nasal cannula, her Sp_{O_2} was 97 percent. Her bedside spirometry results at this time were as follows:

Bedside Spirometry

Parameter*	Predicted	Actual
FVC	2800 mL	2375 mL
FEV_1	>83%	84%
PEFR	400 L/min	345 L/min

*FVC = forced vital capacity; FEV_1 = forced expiratory volume in 1 second; PEFR = peak expiratory flow rate.

The patient continued to improve, and her oxygen therapy, bronchodilator therapy, and IV therapy all discontinued the next morning. Her bedside spirometry results were FVC, 2810 mL; FEV_1, 87 percent; and PEFR, 355 L/min. She was discharged on the afternoon of the second day. During her exit interview, she was instructed to use her metered-dose inhaler about 15 minutes before each gym class.

Discussion

This case illustrates how the measurement of a patient's pulmonary mechanics can serve as an important clinical monitor and the effects and interrelationships of the following on the bronchial airways during a forced expiratory maneuver: the *effort-independent* portion of a forced expiratory maneuver, *dynamic compression,* and the *equal pressure point.*

When the patient was in the emergency department, the fact that her mother knew her daughter's "personal best" PEFR served as an important clinical indicator of the severity of the patient's asthma attack. Today, asthma patients commonly monitor their own PEFR at home to evaluate the severity of an asthmatic episode. Some physicians instruct their patients to call them or to go directly to the hospital when their PEFR decreases to a specific level.

The fact that the respiratory therapist obtained the same bedside spirometry results on the second test demonstrated the effects of *effort-independent flow rate, dynamic compression,* and the *equal pressure point* on the bronchial airways during an FVC maneuver. Remember, approximately the last 70 percent of an FVC maneuver is effort independent because of the dynamic compression of the bronchial airways. When the patient made a stronger muscular effort on the second FVC test, she only moved the equal pressure point (and dynamic compression) of her airways closer to the alveoli—which, in turn, further increased airway resistance and offset any increase in her FVC (see Figure 3–16).

2

Clinical Application Case

A 29-year-old man with no previous history of pulmonary disease presented at his family physician's office complaining of a frequent cough and shortness of breath. He stated that his cough had started about 2 weeks prior to this visit as a result of breathing paint fumes while working in a small and confined area. Even though the patient stated that he had stopped painting in the enclosed area immediately, his cough and his ability to breathe progressively worsened. At the time of this office visit, he had been too ill to work for 2 days. The physician admitted the patient to the hospital and requested a pulmonary consultation.

In the hospital, the patient appeared healthy but in severe respiratory distress. His skin was blue, and his hospital gown was damp from perspiration. He had a frequent and weak cough. During each coughing episode, he produced a moderate amount of thick, white and yellow sputum. His vital signs were blood pressure—155/96 mm Hg, heart rate—90 beats/min, respiratory rate—26 breaths/min, and oral temperature of 37°C. Dull percussion notes were elicited over the lower lobe of the patient's left lung. Course crackles were heard over both lungs during exhalation, and loud bronchial breath sounds were heard over the left lower lobe.

On administration of 4 L/min oxygen via nasal cannula, the patient's arterial oxygen pressure was Pa_{O_2} 63 mm Hg (normal, 80–100 mm Hg). A chest X-ray showed several areas of alveolar collapse *(atelectasis)* throughout the left lower lobe. A pulmonary function study revealed the following results:

Clinical Application Case 2 (continued)

Pulmonary Function Study No. 1

Parameter*	Predicted	Actual
FVC	4600 mL	2990 mL
FEV_1	>83%	67%
$FEV_{200-1200}$	470 L/min	306 L/min
PEFR	>400 L/min	345 L/min
VC	4600 mL	2900 mL
RV	1175 mL	764 mL
FRC	2350 mL	1528 mL

*FVC = forced vital capacity; FEV_1 = forced expiratory volume in first second of an FVC maneuver; $FEF_{200-1200}$ = forced expiratory $flow_{200-1200}$; see text; PEFR = peak expiratory flow rate; VC = vital capacity; RV = residual volume; FRC = functional residual capacity.

In the patient's chart, the physician noted that the excessive bronchial secretions were a result of an acute tracheobronchial tree inflammation (acute bronchitis) caused by the inhalation of noxious paint fumes. The physician also noted that the patches of atelectasis (see Figure 2-24) identified in the patient's left lower lung lobe were most likely caused by excessive airway secretions and mucous plugging.

The respiratory therapist working with the patient obtained a sputum sample and sent it to the laboratory for culture. To help mobilize and clear the excessive bronchial secretions and to offset the mucous plugging, the patient was started on aggressive bronchial hygiene therapy, which consisted of coughing and deep breathing, chest physical therapy, and postural drainage. To treat the atelectasis in the left lower lobe, the patient received lung expansion therapy (hyperinflation therapy), which consisted of incentive spirometry, coughing and deep breathing, and continuous positive airway pressure (CPAP) via a face mask.

Three days later, the patient's general appearance had improved significantly, and he no longer appeared to be in respiratory distress. His skin was pink. He no longer had a cough. When the patient was asked to cough, the cough was strong and nonproductive. At this time, he was receiving antibiotic therapy for a streptococcal infection that had been identified from a sputum culture. His vital signs were blood pressure—116/66 mm Hg, heart rate—64 beats/min, respiratory rate—12 breaths/min, and oral temperature of 37°C. Normal percussion notes were elicited over both lungs. Normal bronchial vesicular breath sounds were heard over both lungs.

On room air, the patient's Pa_{O_2} was 96 mm Hg. A chest X-ray showed no problems. A second pulmonary function study revealed the results shown in the following table. The patient was discharged the next day.

Pulmonary Function Study No. 2

Parameter*	Predicted	Actual
FVC	4600 mL	4585 mL
FEV_1	>83%	83%
$FEV_{200-1200}$	470 L/min	458 L/min
PEFR	>400 L/min	455 L/min
VC	4600 mL	4585 mL
RV	1175 mL	1165 mL
FRC	2350 mL	2329 mL

*FVC = forced vital capacity; FEV_1 = forced expiratory volume in first second of an FVC maneuver; $FEF_{200-1200}$ = forced expiratory $flow_{200-1200}$; see text; PEFR = peak expiratory flow rate; VC = vital capacity; RV = residual volume; FRC = functional residual capacity.

Discussion

This case illustrates both an obstructive and restrictive lung disorder. Because of the excessive bronchial secretions produced by the inhalation of paint fumes and the subsequent streptococcal infection, the patient's FVC, FEV_1, $FEF_{200-1200}$, and PEFR were all decreased at the time of admission.

In addition, the excessive bronchial secretions (and the patient's weak cough effort) caused mucous pooling, and mucous plugging, of the bronchial airways in the left lower lobe. As a result of the mucous plugging, the alveoli distal to the bronchial obstructions could not be ventilated and eventually collapsed. This condition was verified by the chest X-ray, the decreased VC, RV, and FRC, and the loud bronchial breath sounds were auscultated over the left lower lobe

Fortunately, his respiratory problems were reversible with aggressive bronchial hygiene therapy and lung expansion therapy. Once the bronchial secretions were cleared, the obstructive problem was no longer present. This was verified by the increased values shown of the FVC, FEV_1, $FEF_{200-1200}$, and PEFR. When the mucous plugs were cleared and the lungs were re-expanded, the restrictive problem was no longer present. This was verified by the increased values of the VC, FRC, and RV.

Review Questions

1. The volume of air that can be exhaled after a normal tidal volume exhalation is the

A. IRV
B. FRC
C. FVC
D. ERV

2. In an obstructive lung disorder, the

1. FRC is decreased
2. RV is increased
3. VC is decreased
4. IRV is increased
    A. 1 and 3 only
    B. 2 and 3 only
    C. 2 and 4 only
    D. 2, 3, and 4 only

3. The PEFR in normal healthy men ages 20 to 30 years may exceed

A. 300 L/min
B. 400 L/min
C. 500 L/min
D. 600 L/min

4. Which of the following can be obtained from a flow-volume loop study?

1. FVC
2. PEFR
3. FEV_T
4. $FEF_{25\%-75\%}$
    A. 1 and 2 only
    B. 2 and 3 only
    C. 1, 3, and 4 only
    D. 1, 2, 3, and 4

5. The MVV in normal healthy men ages 20 to 30 years is

A. 60 L/min
B. 100 L/min
C. 170 L/min
D. 240 L/min

6. Approximately how much of a forced expiratory maneuver is effort dependent?

A. 20%
B. 30%
C. 40%
D. 50%

7. Which of the following forced expiratory measurements reflects the status of medium-sized to small-sized airways?

A. $FEF_{200-1200}$
B. PEFR
C. MVV
D. $FEF_{25\%-75\%}$

8. Normally, the percentage of the total volume exhaled during an FEV_1 by a 20-year-old individual is

A. 60%
B. 83%
C. 94%
D. 97%

9. Which of the following forced expiratory measurements is a good index of the integrity of large airway function?

A. FEV_T
B. $FEF_{200-1200}$
C. $FEF_{25\%-75\%}$
D. MVV

10. The residual volume/total lung capacity ratio in healthy men ages 20 to 30 years is

A. 15%
B. 20%
C. 25%
D. 30%

11. A 73-year-old man with a long history of smoking demonstrates the following clinical data on a pulmonary function test (PFT):

Pulmonary Function Test

PFT	Below Normal	Normal	Above Normal
VC	X		
RV			X
FRC			X
ERV	X		
FEVT	X		
$FEV_{1\%}$	X		
$FEF_{25\%-75\%}$	X		
PEFR	X	X	
MVV	X	X	

Based on the information shown, the patient appears to have

A. An obstructive lung disorder
B. A restrictive lung disorder
C. Both obstructive and restrictive lung disorders
D. Neither an obstructive nor restrictive lung disorder

Clinical Application Questions

Case 1

1. When the patient was in the emergency department, what pulmonary function measurement served as an important clinical indicator of the severity of the patient's asthma attack?

   ____

2. The fact that the respiratory therapist obtained the same bedside spirometry results on the second test demonstrated the presence of which three physiologic effects?

   ____

   ____

   ____

3. When the patient made a stronger muscular effort on the second FVC test, she only moved the equal pressure point of her airways

   ____

   ____

Case 2

1. This patient demonstrated both obstructive and restrictive lung disorders. During the first part of the case, which pulmonary function studies verified that the patient had an obstructive pulmonary disorder?

   ____

   ____

   ____

2. Which pulmonary function studies verified that the patient had a restrictive pulmonary disorder?

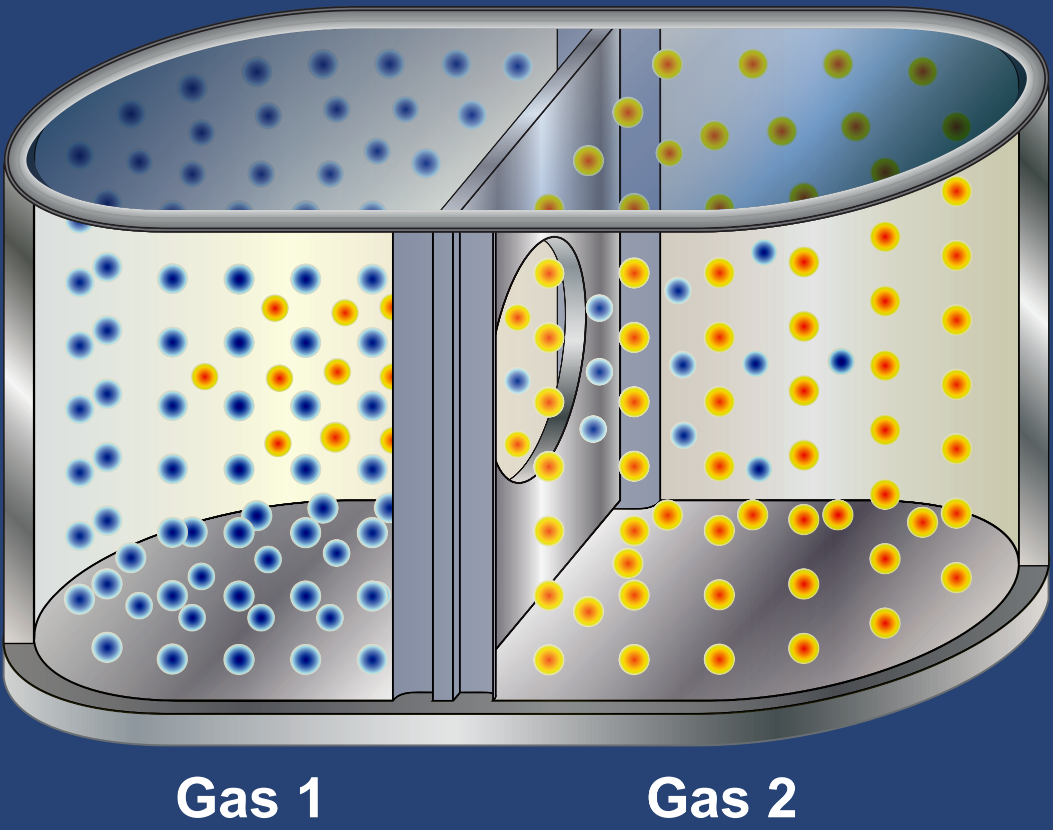
   ____

   ____

   ____

3. After aggressive bronchial hygiene therapy and lung expansion therapy, the patient's FEV_1 (increased ________; decreased ________; remained the same ________), and the RV (increased ________; decreased ________; remained the same ________).

Gas Diffusion



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CHAPTER 4

The Diffusion of Pulmonary Gases

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe Dalton's law.
2. Explain how Dalton's law relates to the partial pressure of atmospheric gases.
3. Identify the percentage and partial pressure of the gases that compose the barometric pressure.
4. Differentiate between pressure gradients and diffusion gradients.
5. Identify the partial pressure of the gases in the air, alveoli, and blood.
6. Calculate the *ideal alveolar gas equation.*
7. Name the nine major structures of the *alveolar-capillary membrane* through which a gas molecule must diffuse.
8. Describe how oxygen and carbon dioxide normally diffuse across the alveolar-capillary membrane.
9. Explain how *Fick's law* relates to gas diffusion.
10. Describe how Henry's law and Graham's law relate to the diffusion constants in Fick's law.
11. Define *perfusion limited,* and explain how it relates to a gas such as nitrous oxide.
12. Define *diffusion limited,* and explain how it relates to a gas such as carbon monoxide.
13. Describe how oxygen can be classified as perfusion or diffusion limited.

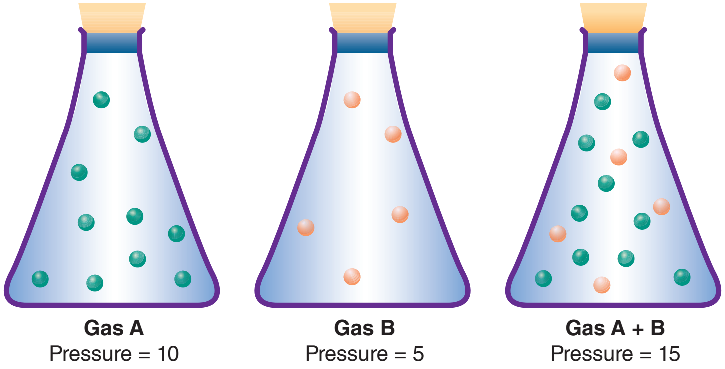
Introduction

As described in Chapter 2, the flow of air between the atmosphere and the alveoli occurs as a result of pressure gradients created by the diaphragm during inspiration and expiration. This mechanism of ventilation moves oxygenated air from the atmosphere to the alveoli during inspiration and carbon dioxide from the alveoli to the external environment during expiration.

The mechanics of ventilation, however, only moves bulk amounts of air in and out of the lungs. The next step in the process of respiration is the movement of gases across the alveolar-capillary membrane (AC—membrane). This process occurs by what is called **gas diffusion**.

To fully appreciate *gas diffusion,* the reader must understand (1) **Dalton's law**; (2) the **partial pressures of atmospheric gases**; and (3) the fundamental differences between (a) **pressure gradients**, which move gas in and out of the lungs, and (b) **diffusion gradients**, which move gas across the alveolar-capillary membrane.

FIGURE 4-1 Dalton's law.



Dalton's Law

According to **Dalton's law**—the **law of partial pressures**,[1,2] the total pressure exerted by a mixture of gases is equal to the sum of the pressures exerted independently by each gas in the mixture. In addition, the pressure exerted by each gas—its partial pressure—is directly proportional to the percentage of that gas in the gas mixture. For example, if 10 molecules of gas are enclosed in a container, the total pressure may be expressed as 10; if 5 molecules of a different gas are enclosed in another container of equal volume, the total pressure may be expressed as 5; if both these gases are enclosed in a container of equal volume, the total pressure may be expressed as 15 (Figure 4–1).

It should be emphasized that the pressure produced by a particular gas is completely unaffected by the presence of another gas. Each gas in a mixture will individually contribute to the total pressure created by the mixture of gases.

Partial Pressures of Atmospheric Gases

The earth's atmospheric gases consist of nitrogen (N_2), oxygen (O_2), carbon dioxide (CO_2), and other trace gases (e.g., argon). Because the partial pressure of each gas that surrounds the earth is directly related to its concentration—relative to the barometric pressure (P_B)—the partial pressure of each gas can easily be determined by multiplying the P_B by the percentage of the gas in the atmosphere. For example, because the percentage of oxygen in the atmosphere is about 21 percent—and assuming a normal P_B of 760 mm Hg at sea level—the partial pressure of oxygen is calculated as follows:

Atmospheric $P_{O_2} = 0.21 \times 760 = 159.6$ mm Hg

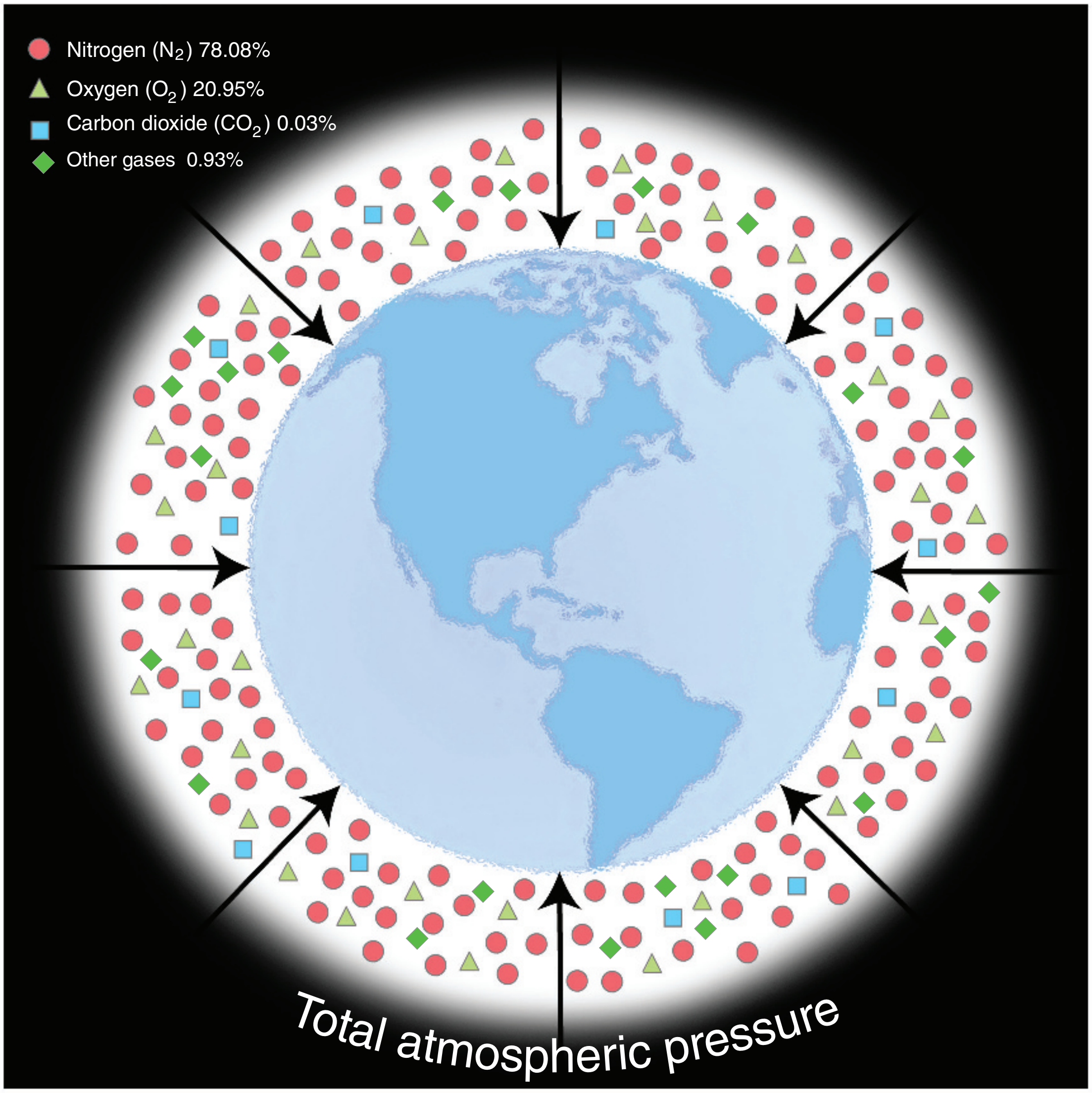
The partial pressure of each of the atmospheric gases—P_{N_2}, P_{O_2}, P_{CO_2}, and some trace gases—collectively make a total atmospheric pressure of 760 mm Hg. Figure 4–2 shows the atmospheric gases, their respective percentages, and the partial pressure of each gas at sea level.

---

[1] The term **partial pressure** refers to the force exerted by one gas in a mixture of gases—or in a liquid.

[2] It should be noted that gas pressure values (e.g., P_{O_2}, P_{CO_2}, N_2) maybe describe as either mm Hg or torr. *Torr* was named after Evangelista Torricelli, an Italian physicist and mathematician, who discovered the principle of the mercury barometer in 1644. In honor of Torricelli, the torr was defined as a unit of pressure equal to 1 mm Hg—i.e., 1 torr = 1 mm Hg.

FIGURE 4-2 Atmospheric gases, their respective percentages, and partial pressure of each gas at sea level.


● Nitrogen (N_2) 78.08%
▲ Oxygen (O_2) 20.95%
■ Carbon dioxide (CO_2) 0.03%
◆ Other gases 0.93%
Total atmospheric pressure

Total atmospheric pressure		P_{N_2}		P_{O_2}		P_{CO_2}		P_{other}
760 mm Hg	=	592.8 mm Hg	+	159.6 mm Hg	+	0.2 mm Hg	+	7 mm Hg
(100%)		(78.08%)		(20.95%)		(0.03%)		(0.93%)

1 mm Hg = 1 torr (see footnote 2, page 186)

The atmospheric pressure decreases with an increase in altitude. This is because the density of the different gases surrounding the earth decreases with increased altitude. As the density of the atmospheric gases decrease, the partial pressure exerted by each gas—for example, the P_{O_2}—also decreases. However, it is important to remember that even though the barometric pressure decreases with the altitude, the concentration of all the atmospheric gases remains the same at both high and low elevations. In other words, the percentage of oxygen is always about 21 percent—both at sea level and at the top of Mt. Everest (29,035 above sea level). What changes at different altitudes are the partial pressures of the atmospheric gases.

Finally, it should be noted that moving in the opposite direction has the reverse effect. That is, the atmospheric pressure increases by 1 atmosphere (760 mm Hg) for each 33 feet of descent (in water) below sea level. For example, at 99 feet below sea level, the total pressure exerted on the body is equal to 4 atmospheres—or 3030 mm Hg. Thus, the partial pressure exerted by each gas in the atmosphere is increased four times. This means the partial pressure of oxygen increases from about 159 mm Hg to 636 mm Hg.[3]

Gas Diffusion—Pressure Gradients versus Diffusion Gradients

As described in Chapter 2, a **pressure gradient** is defined as the movement of gas from an area of high pressure (high concentration) to an area of low pressure (low concentration). A pressure gradient is the primary mechanism responsible for moving air in and out of the lungs during ventilation.

It is important to point out that the pressure gradients generated during ventilation always move a bulk volume of gas in the same direction—either in or out of the lungs. This also means that each individual gas (e.g., N_2, O_2, CO_2, trace gases) moves in the same direction—either in or out of the lungs. As will be described next, individual gas molecules can move in opposite directions during gas diffusion.

Gas diffusion is defined as the movement of "individual gas molecules" from an area of high pressure (high concentration) to an area of low pressure (low concentration). In other words, each individual gas (e.g., N_2, O_2, CO_2) can continue to move independently from the other gases from a high-pressure area to a low-pressure. Individual gas partial pressure differences are known as **diffusion gradients**. Kinetic energy is the driving force responsible for diffusion.

This means that when a volume of gas reaches its destination—for example, the alveoli by means of a pressure gradient, or the alveoli by way of the pulmonary capillary blood flow—each individual gas can move according to its own diffusion gradient. In other words, two different gases can move (diffuse) in opposite directions based on their individual diffusion gradients. For example, under normal circumstances, O_2 diffuses from the alveoli into the pulmonary capillaries, while, at the same time, CO_2 diffuses from the pulmonary capillaries into the alveoli. The diffusion of O_2 and CO_2 continues until the partial pressures of O_2 and CO_2 are in equilibrium.

Clinical Connection 4-1

Pulmonary Disorders That Increase the Alveolar-Capillary Thickness

In the clinical setting, the respiratory therapist will treat countless patients with respiratory disorders that cause the alveolar-capillary membrane thickness to increase (see Figure 4–4). Such pulmonary disorders include pulmonary edema, pneumonia, interstitial lung diseases (e.g., scleroderma, sarcoidosis, or Goodpasture's syndrome), acute respiratory distress syndrome (ARDS), and respiratory distress syndrome (RDS) in newborn infants. In patients who have these conditions, even the total transit time (0.75 second) it takes venous blood to move through the alveolar-capillary system may not be enough for adequate gas exchange. In these cases, the treatment efforts are usually directed at increasing the patient's inspired oxygen concentration.

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[3] For further discussion of pressure at high altitude, refer to Chapter 19, "High Altitudes and Its Effects on the Cardiopulmonary System." For further discussion of pressure at high-pressure environments, refer to Chapter 20, "High-Pressure Environments and Their Effects on the Cardiopulmonary System."

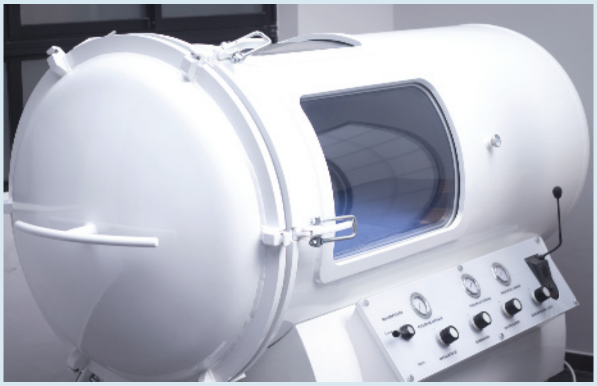
Clinical Connection 4-2

Hyperbaric Oxygen Therapy—A Clinical Application of Henry's Law[4]

Hyperbaric oxygen therapy (HBOT) (also known as hyperbaric medicine) is the therapeutic application of oxygen at pressures greater than 1 atm (Figure 4–3). A patient receiving HBOT is placed in a sealed hyperbaric chamber and exposed to selected oxygen concentrations at 1.5 to 3 times above the normal atmospheric pressure (760 mm Hg). Thus, if a patient receives 100 percent oxygen at 3 atm, the partial pressure of oxygen (P_{O_2}) in the chamber would be 2280 mm Hg ($3 \times 760 = 2280$).

Remember, according to Henry's law, the amount of gas that dissolves in a liquid is directly related to the partial pressure of the gas. In other words, the higher the partial pressure of oxygen (P_{O_2}) in the hyperbaric chamber, the greater the amount of oxygen that will be forced into the patient's pulmonary capillary blood. Although the application of hyperbaric medicine was originally developed to treat underwater divers who were suffering from decompression sickness (the bends), it is now commonly used to treat the following conditions:

FIGURE 4-3 Hyperbaric chamber



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Indications for Hyperbaric Oxygenation

Gas disorders

- Gas embolism
- Decompression sickness

Vascular disorders

- Radiation necrosis
- Diabetic wounds of the lower extremities
- Nonhealing skin grafts
- Crush injuries
- Acute traumatic ischemias
- Thermal burns

Infections

- Clostridial gangrene
- Necrotizing soft-tissue infections (flesh-eating bacteria)
- Refractory osteomyelitis

Oxygen transport disorders

- Carbon monoxide (CO) poisoning
- Cyanide poisoning
- Severe blood loss or anemia

---

[4] Also see related Clinical Connection 19–1, "Hypobaric Sleep and the Athlete in Training."

The Partial Pressures of Gases in the Air, Alveoli, and Blood

Table 4–1 shows the partial pressure of gases in dry air, alveolar gas, arterial blood, and venous blood. Note that even though the total barometric pressure is the same in the atmosphere and in the alveoli, the partial pressure of oxygen in the atmosphere (159 mm Hg) is significantly higher than the partial pressure of oxygen in the alveoli (100 mm Hg). This is because alveolar oxygen must mix—or compete, in terms of partial pressures—with alveolar CO_2 pressure ($P_{A_{CO_2}} = 40$ mm Hg) and alveolar water vapor pressure ($P_{H_2O} = 47$ mm Hg), which are not nearly as high in the atmosphere. In short, by the time the oxygen molecules reach the alveoli, they are diluted by the addition of CO_2 and H_2O molecules. This leads to a decrease in the partial pressure of oxygen in the alveoli ($P_{A_{O_2}}$).

Depending on the surrounding temperature and pressure, water can exist as a liquid, gas, or solid. Water in the gaseous form is called *water vapor,* or *molecular water.* When water vapor is present in a

TABLE 4-1 Partial Pressure (mm Hg)* of Gases in the Air, Alveoli, and Blood**

Gases	Dry Air	Alveolar Gas	Arterial Blood	Venous Blood
P_{O_2}	159.0	100.0	95.0	40.0
P_{CO_2}	0.2	40.0	40.0	46.0
P_{H_2O} (water vapor)	0.0	47.0	47.0	47.0
P_{N_2} (and other gases in minute quantities)	600.8	573.0	573.0	573.0
Total	760.0	760.0	755.0	706.0

* 1 mm Hg = 1 torr
** The values shown are based on standard pressure and temperature.

TABLE 4-2 Relationship between Temperature, Absolute Humidity, and Water Vapor Pressure*

Temperature (Celsius)	Absolute (Maximum) Humidity (mg/L)	Water Vapor Pressure (mm Hg)
37°	44.0	47.0
35°	39.6	42.2
30°	30.4	31.8
27°	25.8	26.7
25°	23.0	23.8
20°	17.3	17.5

* At sea level (760 mm Hg).
1 mm Hg = 1 torr

volume of gas, it behaves according to the gas laws and exerts a partial pressure. Because alveolar gas is 100 percent humidified (saturated) at body temperature, the alveolar gas is assumed to have an *absolute humidity* of 44 mg/L, and a *water vapor pressure* (P_{H_2O}) of 47 mm Hg—regardless of the humidity of the inspired air (Table 4–2).

The Ideal Alveolar Gas Equation

Clinically, the alveolar oxygen tension (PA_{O_2}) can be computed from the **ideal alveolar gas equation**. A useful clinical approximation of the ideal alveolar gas equation is as follows:

$$PA_{O_2} = [PB - P_{H_2O}]FI_{O_2} - Pa_{CO_2}\ (1.25)$$

or

$$PA_{O_2} = [PB - P_{H_2O}]FI_{O_2} - \frac{Pa_{CO_2}}{0.8}$$

where PA_{O_2} is the partial pressure of oxygen in the alveoli, PB is the barometric pressure, P_{H_2O} is the partial pressure of water vapor in the alveoli (P_{H_2O} = 47 mm Hg), FI_{O_2} is the fractional concentration of inspired oxygen, and Pa_{CO_2} is the partial pressure of arterial carbon dioxide. The number 1.25 is a factor that adjusts for alterations in oxygen tension due to variations in the *respiratory exchange ratio* (RR), which is the ratio of the amount of oxygen that moves into the pulmonary capillary blood to the amount of carbon dioxide that moves out of the pulmonary blood and into the alveoli. Normally, about 200 mL/minute of carbon dioxide move into the alveoli while about 250 mL/minute of oxygen move into the pulmonary capillary blood, making the respiratory exchange ratio about 0.8.

Thus, if a patient is receiving an $F_{I_{O_2}}$ of 0.40 on a day when the barometric pressure is 755 mm Hg, and if the Pa_{CO_2} is 55 mm Hg, then the patient's alveolar oxygen tension ($P_{A_{O_2}}$) can be calculated as follows:

$$
\begin{aligned}
P_{A_{O_2}} &= [P_B - P_{H_2O}]F_{I_{O_2}} - Pa_{CO_2}(1.25)\\
&= [755 - 47]0.40 - 55(1.25)\\
&= [708]0.40 - 68.75\\
&= [283.2] - 68.75\\
&= 214.45
\end{aligned}
$$

Clinically, when the Pa_{CO_2} is less than 60 mm Hg, and when the patient is receiving oxygen therapy greater than 0.6, the following simplified version of the alveolar gas equation may be used:

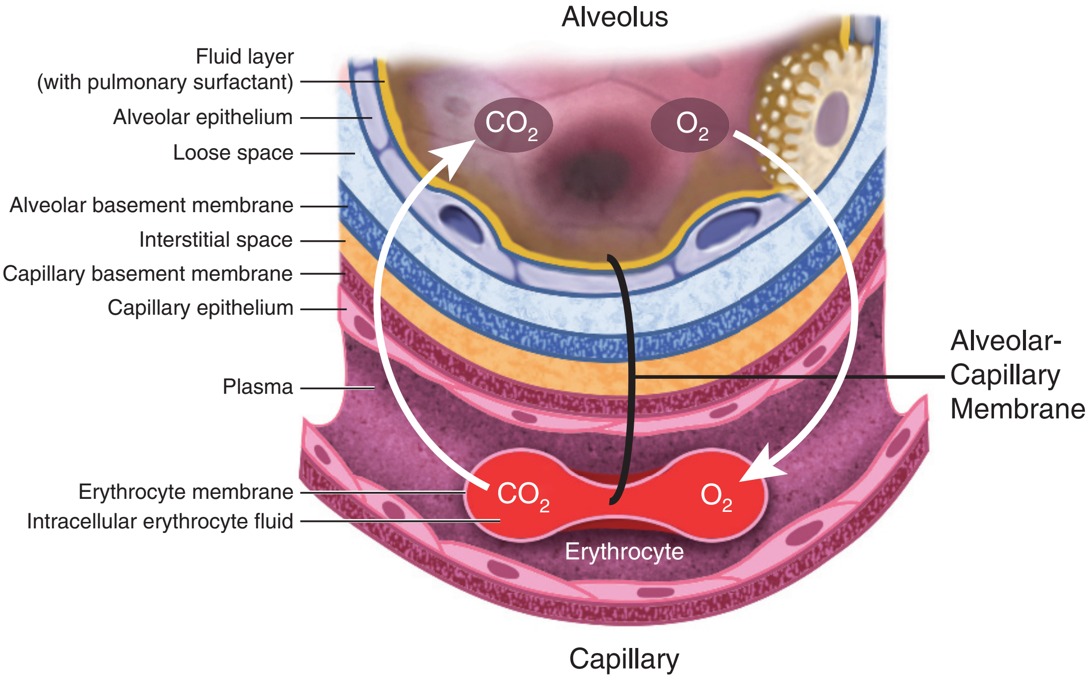
$$P_{A_{O_2}} = [P_B - P_{H_2O}]F_{I_{O_2}} - Pa_{CO_2}$$

The Diffusion of Pulmonary Gases

The process of diffusion is the passive movement of gas molecules from an area of high partial pressure to an area of low partial pressure until both areas are equal in pressure. Once equilibrium occurs, diffusion ceases.

In the lungs, a gas molecule must diffuse through the alveolar-capillary membrane (Figure 4–4), which is composed of (1) the liquid lining the intra-alveolar membrane, (2) the alveolar epithelial cell, (3) the basement membrane of the alveolar epithelial cell, (4) loose connective tissue (the interstitial space), (5) the basement membrane of the capillary endothelium, (6) the capillary endothelium, (7) the plasma in the capillary blood, (8) the erythrocyte membrane, and (9) the intracellular fluid in the erythrocyte until a

FIGURE 4–4 The major barriers of the alveolar-capillary membrane through which a gas molecule must diffuse.


Alveolus
Fluid layer (with pulmonary surfactant)
Alveolar epithelium
Loose space
Alveolar basement membrane
Interstitial space
Capillary basement membrane
Capillary epithelium
Plasma
Erythrocyte membrane
Intracellular erythrocyte fluid
CO_2
O_2
CO_2
O_2
Erythrocyte
Alveolar-Capillary Membrane
Capillary

hemoglobin molecule is encountered. The thickness of these physical barriers is between 0.2 and 2.5 μm. Under normal circumstances, this is a negligible barrier to the diffusion of oxygen and carbon dioxide.

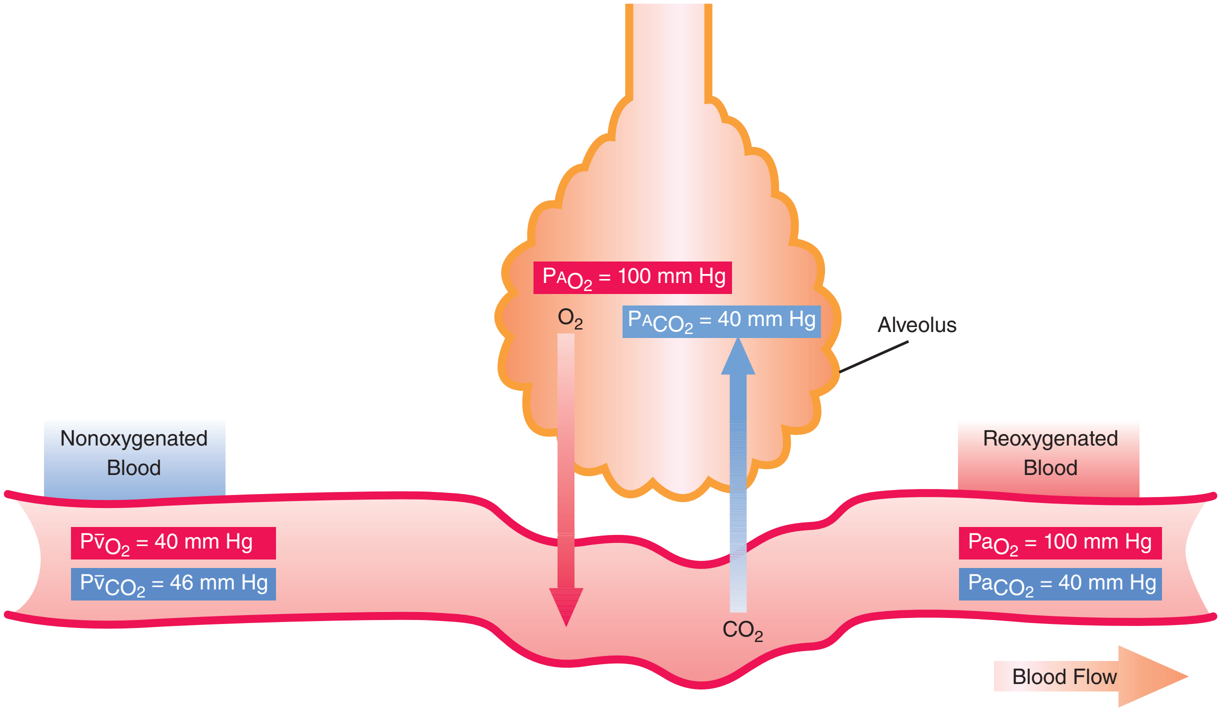
Oxygen and Carbon Dioxide Diffusion across the Alveolar-Capillary Membrane

In the healthy resting individual, venous blood entering the alveolar-capillary system has an average oxygen tension ($P\bar{v}_{O_2}$) of 40 mm Hg and an average carbon dioxide tension ($P\bar{v}_{CO_2}$) of 46 mm Hg. As blood passes through the capillary, the average alveolar oxygen tension ($P_{A_{O_2}}$) is about 100 mm Hg, and the average alveolar carbon dioxide tension ($P_{A_{CO_2}}$) is about 40 mm Hg (see Table 4–1).

Thus, when venous blood enters the alveolar-capillary system, there is an oxygen pressure gradient of about 60 mm Hg and a carbon dioxide pressure gradient of about 6 mm Hg. As a result, oxygen molecules diffuse across the alveolar-capillary membrane into the blood while, at the same time, carbon dioxide molecules diffuse out of the capillary blood and into the alveoli (Figure 4–5).[5]

The diffusion of oxygen and carbon dioxide will continue until equilibrium is reached; this is usually accomplished in about 0.25 second. Under normal resting conditions, the total transit time for blood to move through the alveolar-capillary system is about 0.75 second. Thus, the diffusion of oxygen and carbon dioxide is completed in about one-third of the time available (Figure 4–6).

FIGURE 4-5 Normal gas pressures for oxygen (O_2) and carbon dioxide (CO_2) as blood moves through the alveolar-capillary membrane. $P\bar{v}_{O_2}$ = partial pressure of oxygen in mixed venous blood; $P\bar{v}_{CO_2}$ = partial pressure of carbon dioxide in mixed venous blood; $P_{A_{O_2}}$ = partial pressure of oxygen in alveolar gas; $P_{A_{CO_2}}$ = partial pressure of carbon dioxide in alveolar gas; Pa_{O_2} = partial pressure of oxygen in arterial blood; Pa_{CO_2} = partial pressure of carbon dioxide in arterial blood.



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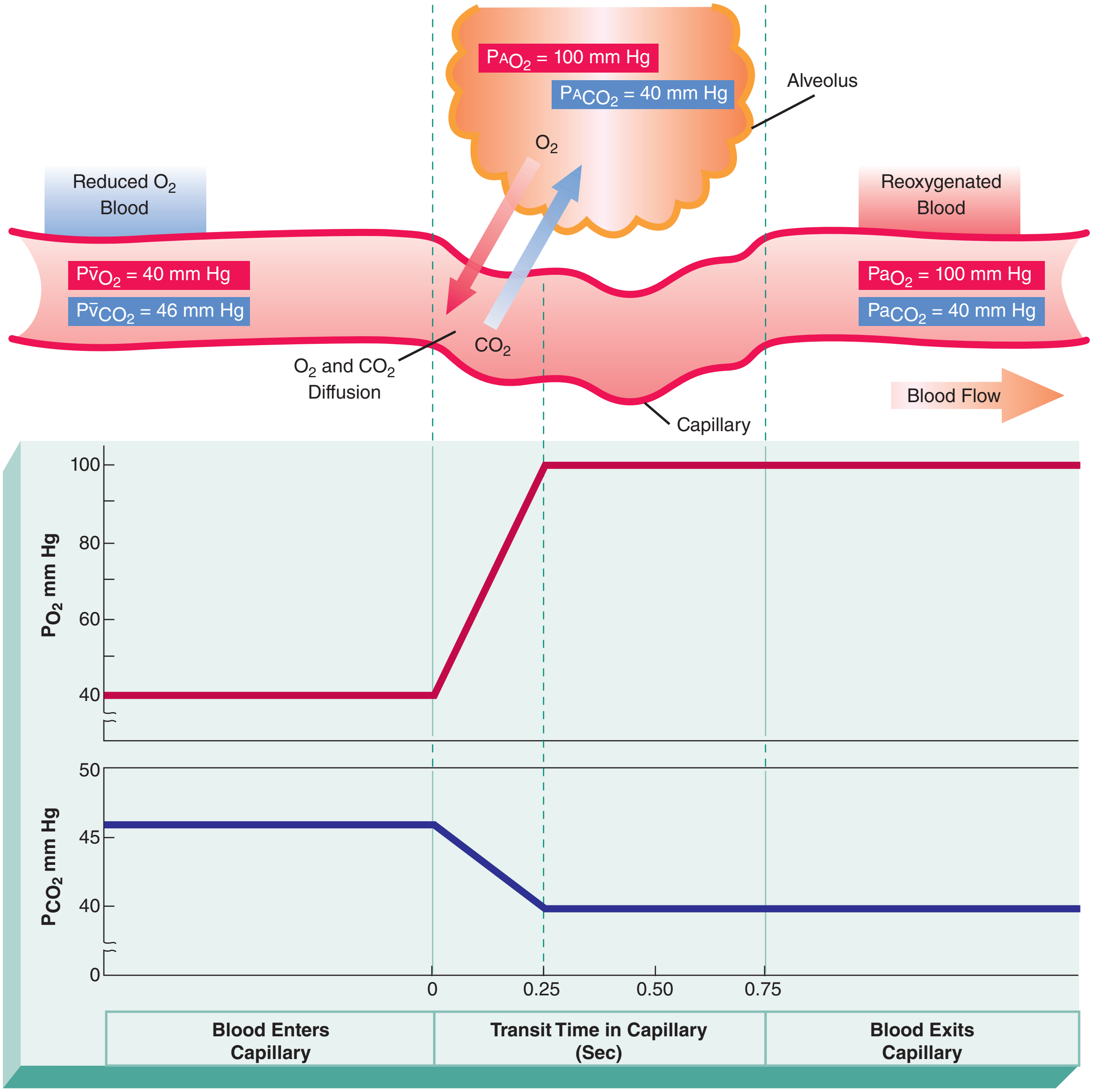
[5] The exhaled P_{CO_2} leaving at the level of the mouth is about 35 mm Hg because of different alveolar emptying rates.

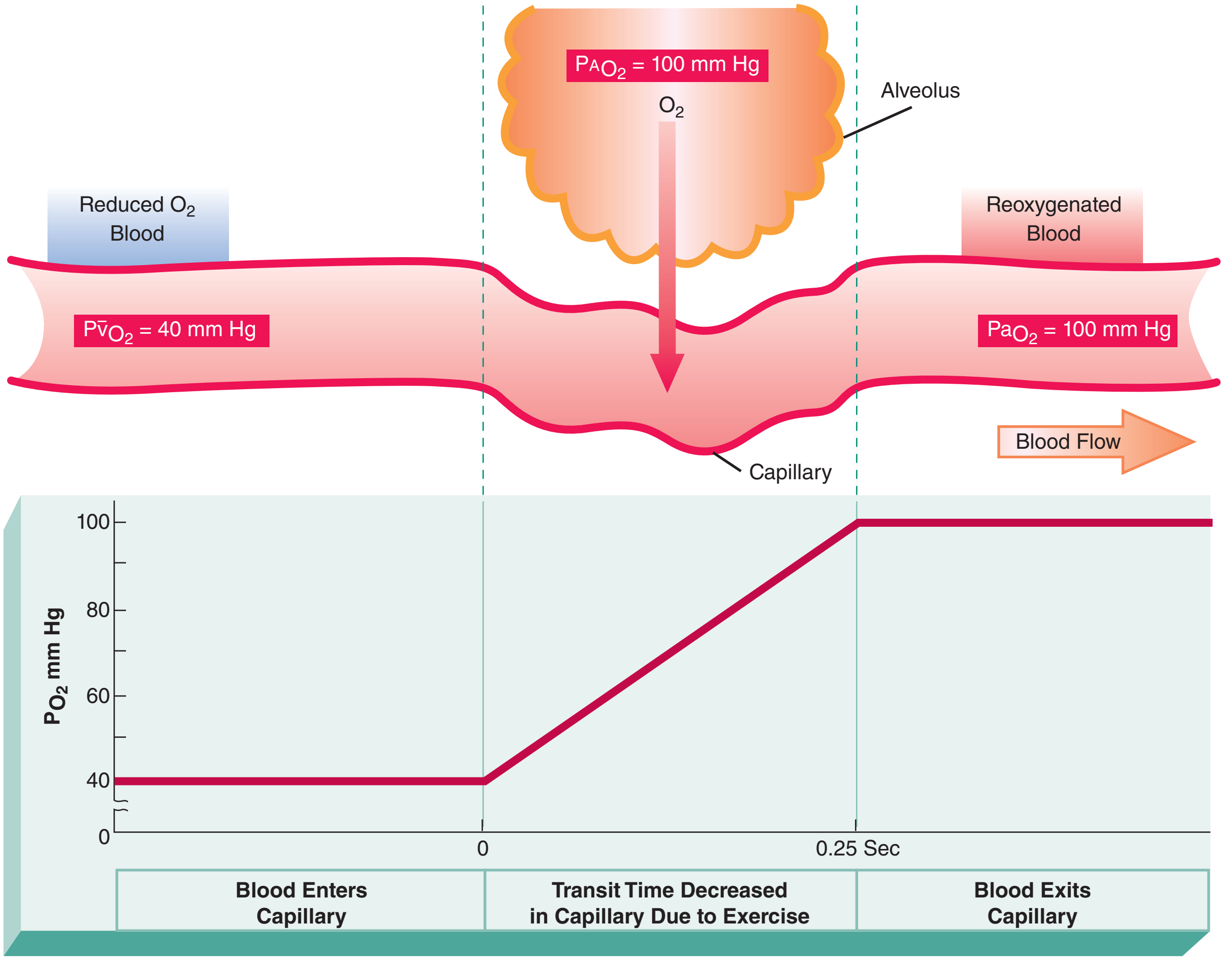
FIGURE 4-6 Under normal resting conditions, blood moves through the alveolar-capillary membrane in about 0.75 second. The oxygen pressure (P_{O_2}) and carbon dioxide pressure (P_{CO_2}) reach equilibrium in about 0.25 second—one-third of the time available. $P\bar{v}_{O_2}$ = partial pressure of oxygen in mixed venous blood; $P\bar{v}_{CO_2}$ = partial pressure of carbon dioxide in mixed venous blood; $P_{A_{O_2}}$ = partial pressure of oxygen in alveolar gas; $P_{A_{CO_2}}$ = partial pressure of carbon dioxide in alveolar gas; Pa_{O_2} = partial pressure of oxygen in arterial blood; Pa_{CO_2} = partial pressure of carbon dioxide in arterial blood.



PAO2 = 100 mm Hg
PACO2 = 40 mm Hg
Alveolus
O2
Reduced O2 Blood
Reoxygenated Blood
Pv̄O2 = 40 mm Hg
Pv̄CO2 = 46 mm Hg
PaO2 = 100 mm Hg
PaCO2 = 40 mm Hg
CO2
O2 and CO2 Diffusion
Capillary
Blood Flow
PO2 mm Hg
100
80
60
40
PCO2 mm Hg
50
45
40
0
0
0.25
0.50
0.75
Blood Enters Capillary
Transit Time in Capillary (Sec)
Blood Exits Capillary

In exercise, however, blood passes through the alveolar-capillary system at a much faster rate and, therefore, the time for gas diffusion decreases (i.e., the time available for gas diffusion is <0.75 second). In the healthy lung, oxygen equilibrium usually occurs in the alveolar-capillary system during exercise—in spite of the shortened transit time (Figure 4–7). In the presence of certain pulmonary diseases, however, the time available to achieve oxygen equilibrium in the alveolar-capillary system may not be adequate. Such diseases include pulmonary edema, pneumonia (alveolar consolidation), and interstitial lung diseases (Figure 4–8).

FIGURE 4-7 During exercise or stress, the total transit time for blood through the alveolar-capillary membrane is less than normal (normal = 0.75 second). In the healthy individual, however, oxygen equilibrium usually occurs. $P\bar{v}_{O_2}$ = partial pressure of oxygen in mixed venous blood; PA_{O_2} = partial pressure of oxygen in alveolar gas; Pa_{O_2} = partial pressure of oxygen in arterial blood.

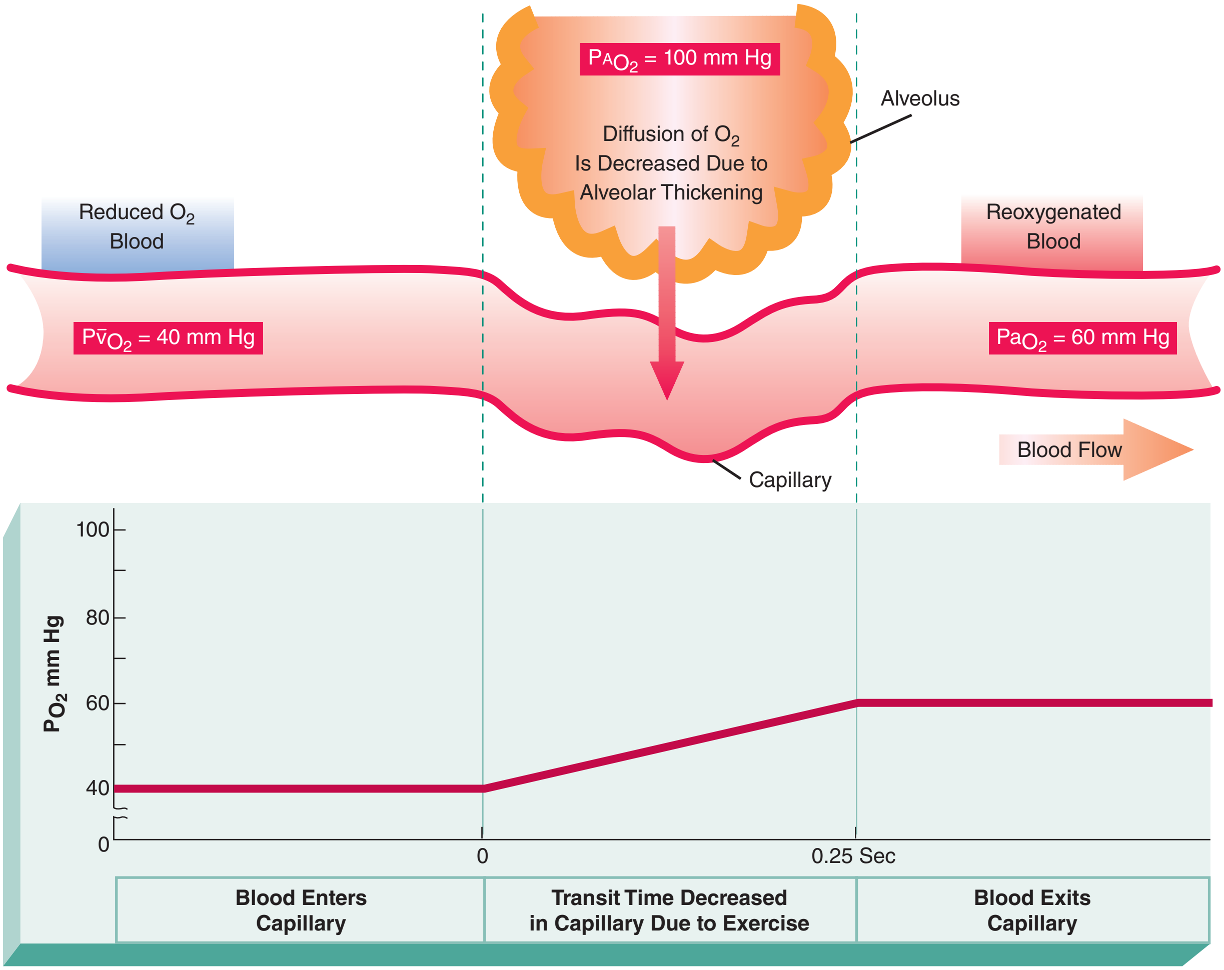

PA_{O_2} = 100 mm Hg
O_2
Alveolus
Reduced O_2 Blood
Reoxygenated Blood
$P\bar{v}_{O_2}$ = 40 mm Hg
Pa_{O_2} = 100 mm Hg
Blood Flow
Capillary
100
80
60
40
0
P_{O_2} mm Hg
0
0.25 Sec
Blood Enters Capillary
Transit Time Decreased in Capillary Due to Exercise
Blood Exits Capillary

Clinical Connection 4-3

Oxygen Toxicity

Although breathing high concentrations of oxygen is safe for short periods of time, what is called **oxygen toxicity** can develop within 24 hours in response to high partial pressures of inspired oxygen (P_{O_2}) and with longer exposure times to inspired oxygen concentrations (FI_{O_2}) above 0.50. In other words, the higher the inspired P_{O_2} and the longer the exposure, the more likely oxygen toxicity will develop. Oxygen toxicity affects the lungs and the central nervous system. Pulmonary effects include tracheobronchitis, substernal chest pain, atelectasis, decreased vital capacity, decreased lung compliance, and decreased diffusing capacity. Central nervous system effects include tremors, twitching, convulsions, coma, and death. Central nervous system effects tend to occur only when a patient is breathing oxygen at pressures greater than 1 atm (hyperbaric medicine).

FIGURE 4-8 When the rate of diffusion is decreased because of alveolar thickening, oxygen equilibrium will likely not occur when the total transit time is decreased as a result of exercise or stress. $P\bar{v}_{O_2}$ = partial pressure of oxygen in mixed venous blood; PA_{O_2} = partial pressure of oxygen in alveolar gas; Pa_{O_2} = partial pressure of oxygen in arterial blood.


PAO2 = 100 mm Hg
Diffusion of O2 Is Decreased Due to Alveolar Thickening
Alveolus
Reduced O2 Blood
Reoxygenated Blood
Pv̄O2 = 40 mm Hg
PaO2 = 60 mm Hg
Capillary
Blood Flow
PO2 mm Hg
100
80
60
40
0
0
0.25 Sec
Blood Enters Capillary
Transit Time Decreased in Capillary Due to Exercise
Blood Exits Capillary

Gas Diffusion According to Fick's Law

Fick's Law

The diffusion of gas takes place according to Fick's law, which is written as follows:

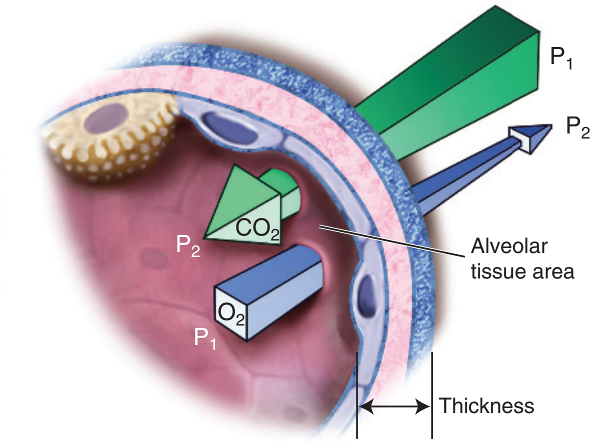
$$\dot{V}\,\text{gas} \approx \frac{A \cdot D \cdot (P_1 - P_2)}{T}$$

where $\dot{V}$ gas is the amount of gas that diffuses from one point to another, A is the surface area, D is the diffusion constant, $P_1 - P_2$ is the difference in partial pressure between two points, and T is the thickness.

The law states that the rate of gas transfer across a sheet of tissue is directly proportional to the surface area of the tissue, to the diffusion constants, and to the difference in partial pressure of the gas between the two sides of the tissue, and it is inversely proportional to the thickness of the tissue (Figure 4–9).

The diffusion constant (D), noted in Fick's law, is determined by Henry's law and Graham's law.

FIGURE 4-9 Fick's law.



$$\boxed{\dot{V}_{gas} = \frac{AD\,(P_1 - P_2)}{T}}$$

Henry's Law

Henry's law states that the amount of a gas that dissolves in a liquid at a given temperature is proportional to the partial pressure of the gas. The amount of gas that can be dissolved by 1 mL of a given liquid at standard pressure (760 mm Hg) and specified temperature is known as the *solubility coefficient* of the liquid. At 37°C and 760 mm Hg pressure, the solubility coefficient of oxygen is 0.0244 mL/mm Hg/mL H_2O. The solubility coefficient of carbon dioxide is 0.592 mL/mm Hg/mL H_2O. The solubility coefficient varies inversely with temperature (i.e., if the temperature rises, the solubility coefficient decreases in value).

On the basis of the solubility coefficients of oxygen and carbon dioxide, it can be seen that in a liquid medium (e.g., alveolar-capillary membrane) carbon dioxide is more soluble than oxygen:

$$\frac{\text{Solubility of } CO_2}{\text{Solubility of } O_2} = \frac{0.592}{0.0244} = \frac{24}{1}$$

Graham's Law

Graham's law states that the rate of diffusion of a gas through a liquid is (1) directly proportional to the solubility coefficient of the gas and (2) indirectly proportional to the square root of the gram-molecular weight (GMW) of the gas. In comparing the relative rates of diffusion to oxygen (GMW = 32) and carbon dioxide (GMW = 44), it can be seen that because oxygen is the lighter gas, it moves faster than carbon dioxide:

$$\frac{\text{Diffusion rate for } CO_2}{\text{Diffusion rate for } O_2} = \frac{\sqrt{\text{GMW } O_2}}{\sqrt{\text{GMW } CO_2}} = \frac{\sqrt{32}}{\sqrt{44}} = \frac{5.6}{6.6}$$

By combining Graham's and Henry's laws, it can be said that the rates of diffusion of two gases are directly proportional to the ratio of their solubility coefficients, and inversely proportional to the ratio of their gram-molecular weights. For example, when the two laws are used to determine the relative rates of diffusion of carbon dioxide and oxygen, it can be seen that carbon dioxide diffuses about 20 times faster than oxygen.

$$\frac{\text{Diffusion rate for } CO_2}{\text{Diffusion rate for } O_2} = \frac{5.6 \times 0.592}{6.6 \times 0.0244} = \frac{20}{1}$$

To summarize, the diffusion constant (D) for a particular gas is directly proportional to the solubility coefficients (S) of the gas, and inversely proportional to the square root of the GMW of the gas:

$$D = \frac{S}{\sqrt{GMW}}$$

Mathematically, when the two diffusion factors (i.e., the solubility and square root of the gmw of the gas) are applied to Fick's law, the formula can be written as:

$$\dot{V}\,\text{gas} \approx \frac{A \cdot S \cdot (P_1 - P_2)}{\sqrt{GMW} \times T}$$

Clinical Application of Fick's Law

Clinically, Fick's law applies to the following general statements:

- The area (A) component of the law is verified in that a decreased alveolar surface area (e.g., caused by alveolar collapse or alveolar fluid) decreases the ability of oxygen to enter the pulmonary capillary blood.
- The $P_1 - P_2$ portion of the law is confirmed in that a decreased alveolar oxygen pressure ($P_{A_{O_2}}$ or P_1) (e.g., caused by high altitudes or alveolar hypoventilation) reduces the diffusion of oxygen into the pulmonary capillary blood.
- The thickness (T) factor is confirmed in that an increased alveolar tissue thickness (e.g., caused by alveolar fibrosis or alveolar edema) reduces the movement of oxygen across the alveolar-capillary membrane.

Fick's law also suggests how certain adverse pulmonary conditions may be improved. For example, when a patient's oxygen diffusion rate is decreased because of alveolar thickening, the administration of oxygen therapy will be beneficial. As the patient's fractional concentration of inspired oxygen ($F_{I_{O_2}}$) increases, the patient's alveolar oxygen pressure (i.e., $P_{A_{O_2}}$ or the P_1) also increases, causing the movement of oxygen across the alveolar-capillary membrane to increase.

Clinical Connection 4-4

The Clinical Case Applications of Fick's Law

In the Clinical Application Case 1 (page 206), the respiratory therapist is called to care for a 68-year-old man in severe left ventricular heart failure and pulmonary edema (see Figure 4–17). This case illustrates both the undesirable effects, and the therapeutic effects, associated with Fick's law. This clinical event describes how the pathologic changes associated with pulmonary edema increase the thickness of the alveolar-capillary (AC) membrane. Because gas diffusion ($\dot{V}$) is indirectly related to thickness (T), the diffusion of oxygen across the AC membrane decreases. Case 1 further describes how the respiratory therapist treats the patient's low oxygenation status by increasing the patient's alveolar oxygen pressure (Pa_{O_2}) or P_1 of Fick's law. Because gas diffusion is directly related to $P_1 - P_2$, the diffusion of gas across the patient's AC membrane is enhanced.

In the Clinical Application Case 2 (page 207), the respiratory therapist is called to treat a 78-year-old woman with a long history of chronic interstitial lung disease (alveolar thickening and fibrosis) who is in respiratory distress. This case illustrates both the acute and chronic harmful effects of an increased AC-membrane thickness (T), and the therapeutic benefits of increasing the patient's $P_{A_{O_2}}$ (P_1).

Clinical Connection 4-5

Respiratory Disorders That Decrease the Alveolar Surface Area

A number of respiratory disorders can drastically reduce the alveolar surface area (the "A" component in Fick's law). For example, because emphysema breaks down the walls of adjacent alveoli and pulmonary capillaries, the alveoli merge together into large air sacs (called *bullae*). Because emphysema destroys both the alveoli and pulmonary capillaries, the alveolar surface area decreases. Increasing the patient's $P_{A_{O_2}}$ (P_1) can be helpful with these patients. The alveolar surface area is also reduced in pulmonary disorders associated with excessive tracheobronchial tree secretions or tumors, which block air flow to the alveoli, and alveolar collapse (e.g., pleural effusion, pneumothorax, or excessive airway secretions).

Perfusion-Limited Gas Flow

Perfusion limited means that the transfer of gas across the alveolar wall is a function of the amount of blood that flows past the alveoli. Nitrous oxide (N_2O) is an excellent gas to illustrate this concept. When N_2O moves across the alveolar wall and into the blood, it does not chemically combine with hemoglobin. Because of this, the partial pressure of N_2O in the blood plasma rises very quickly. It is estimated that the partial pressure of N_2O will equal that of the alveolar gas when the blood is only about one-tenth of the way through the alveolar-capillary system (Figure 4–10). Once the partial pressures of the N_2O in the blood and in the alveolar gas are equal, the diffusion of N_2O stops. In order for the diffusion of N_2O to resume, additional blood must enter the alveolar-capillary system. The rate of perfusion, therefore, determines the amount of diffusion of N_2O.

Clinical Connection 4-6

Decreased $D_{L_{CO}}$—The Classic Pulmonary Function Diagnostic Sign of Emphysema

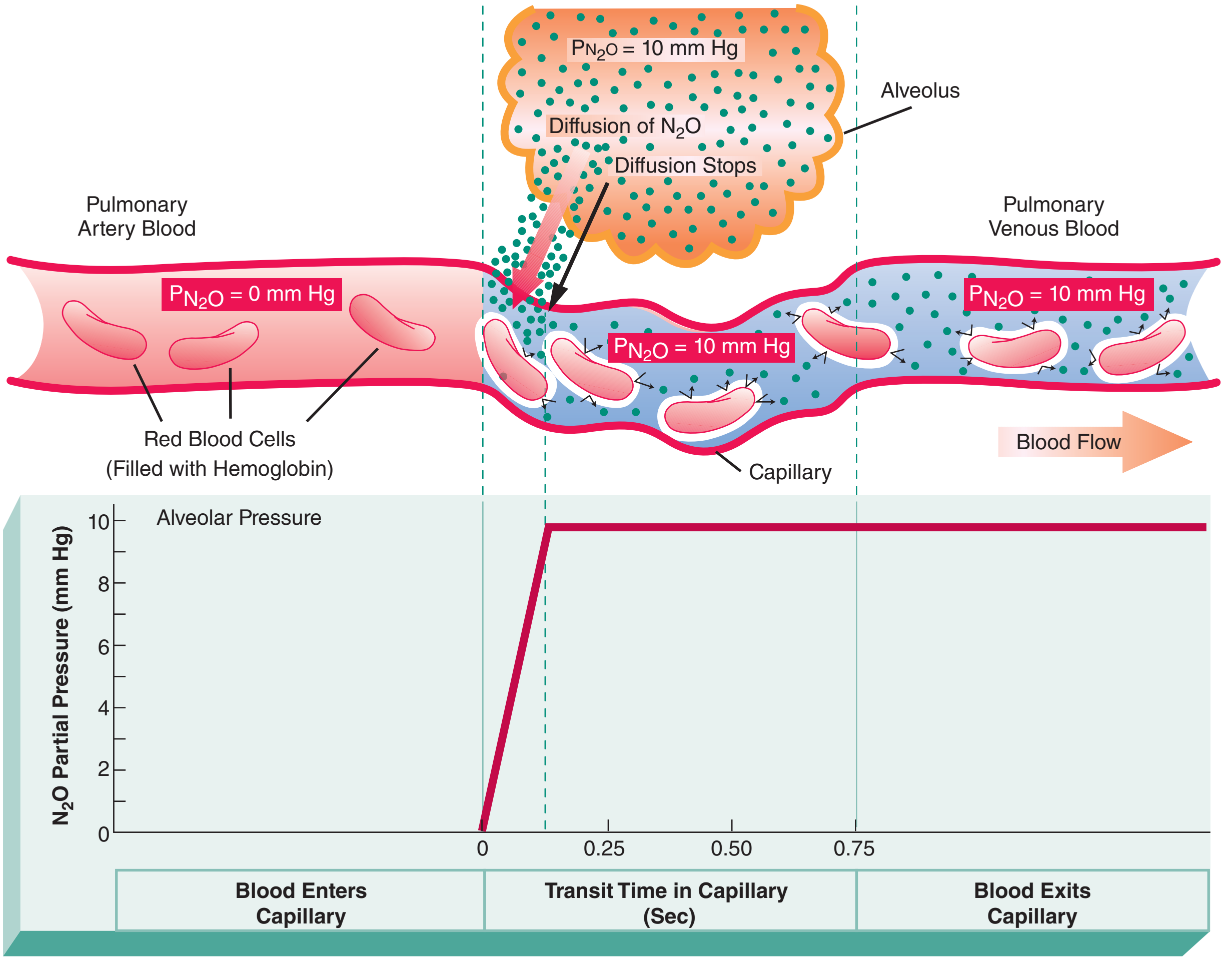
Clinically, the signs and symptoms associated with emphysema appear very similar to other chronic obstructive pulmonary disorders. For example, at the bedside, patients with emphysema, chronic bronchitis, or cystic fibrosis may all demonstrate a barrel chest, digital clubbing, or diminished breath sounds. Their arterial blood gas values generally reveal low oxygenation levels and high carbon dioxide levels. All patients with significant COPD demonstrate elevated RVs and FRC (caused by air trapping) and decreased FVC and FEV_1 values (caused by increased airway resistance). However, the classic pulmonary function diagnostic test that verifies that a patient has emphysema is a decreased $D_{L_{CO}}$. This is because of the alveolar-capillary destruction (decreased alveolar surface area) associated with emphysema. Alveolar-capillary destruction is not associated with the other chronic obstructive pulmonary disorders.

In addition to emphysema, there are other lung disorders associated with a decreased $D_{L_{CO}}$ value. The following table provides three useful ways to correlate a patient's $D_{L_{CO}}$ value, lung volumes (usually the FRC), and specific lung abnormalities:

Clinical Connection 4-6, Continued

Lung Abnormality	**DL_{CO} and FRC**	**Pulmonary Disorder**
Hyperinflation and decreased DL_{CO}	Decreased DL_{CO} Increased FRC	Emphysema, etc. (COPD)
Hypoinflation and decreased DL_{CO}	Decreased DL_{CO} Decreased FRC	Restrictive lung disease (e.g., pulmonary edema, chronic interstitial lung disease)
Normal lung volume and decreased DL_{CO}	Decreased DL_{CO} Normal FRC	Pulmonary embolism

FIGURE 4-10 Nitrous oxide (N_2O) quickly equilibrates with pulmonary blood. When equilibrium occurs, the diffusion of N_2O stops. In order for the diffusion of N_2O to resume, fresh blood (pulmonary artery blood) must enter the alveolar-capillary system. This phenomenon is called *perfusion limited.* P_{N_2O} = partial pressure of N_2O in the blood.



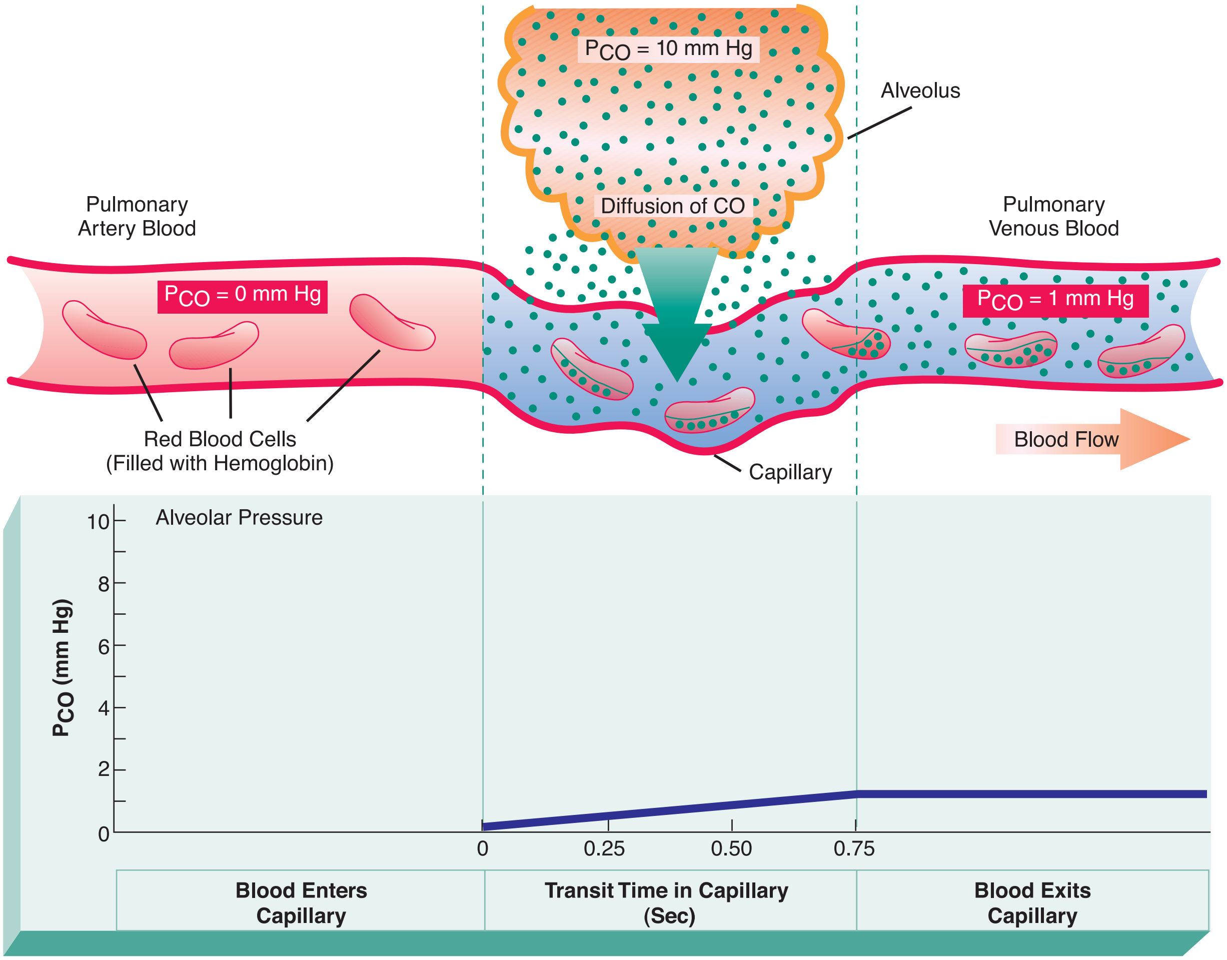
PN_2O = 10 mm Hg
Diffusion of N_2O
Diffusion Stops
Alveolus
Pulmonary Artery Blood
Pulmonary Venous Blood
PN_2O = 0 mm Hg
PN_2O = 10 mm Hg
PN_2O = 10 mm Hg
Red Blood Cells (Filled with Hemoglobin)
Capillary
Blood Flow
Alveolar Pressure
N_2O Partial Pressure (mm Hg)
10
8
6
4
2
0
0
0.25
0.50
0.75
Blood Enters Capillary
Transit Time in Capillary (Sec)
Blood Exits Capillary

Diffusion-Limited Gas Flow

Diffusion limited means that the movement of gas across the alveolar wall is a function of the integrity of the alveolar-capillary membrane itself. Carbon monoxide (CO) is an excellent gas to illustrate this concept. When CO moves across the alveolar wall and into the blood, it rapidly enters the red blood cells (RBCs) and tightly bonds to hemoglobin (CO has an affinity for hemoglobin that is about 210 times greater than that of oxygen).

Note that when gases are in chemical combination with hemoglobin, they no longer exert a partial pressure. Thus, because CO has a strong chemical attraction to hemoglobin, most of the CO enters the RBCs, combines with hemoglobin, and no longer exerts a partial pressure in the blood plasma. Because there is no appreciable partial pressure of CO in the blood plasma at any time (i.e., $P_1 - P_2$ stays constant), only the diffusion characteristics of the alveolar-capillary membrane, not the amount of blood flowing through the capillary, limit the diffusion of CO (Figure 4–11).

FIGURE 4-11 Carbon monoxide (CO) rapidly bonds to hemoglobin and, thus, does not generate an appreciable partial pressure (P_{CO}) in the plasma. As a result of this chemical relationship, blood flow (perfusion) does not limit the rate of CO diffusion. When the alveolar-capillary membrane is abnormal (e.g., in alveolar fibrosis), however, the rate of CO diffusion decreases. This phenomenon is called *diffusion limited.* In essence, diffusion limited means that the structure of the alveolar-capillary membrane alone limits the rate of gas diffusion.


PCO = 10 mm Hg
Alveolus
Diffusion of CO
Pulmonary Artery Blood
PCO = 0 mm Hg
Pulmonary Venous Blood
PCO = 1 mm Hg
Red Blood Cells (Filled with Hemoglobin)
Capillary
Blood Flow
Alveolar Pressure
PCO (mm Hg)
10
8
6
4
2
0
0
0.25
0.50
0.75
Blood Enters Capillary
Transit Time in Capillary (Sec)
Blood Exits Capillary

This property makes CO an excellent gas for evaluating the lung's ability to diffuse gases and is used in what is called the *diffusion capacity of carbon monoxide* ($D_{L_{CO}}$) test. The $D_{L_{CO}}$ test measures the amount of CO that moves across the alveolar-capillary membrane into the blood in a given time. In essence, this test measures the physiologic effectiveness of the alveolar-capillary membrane. The normal diffusion capacity of CO is 25 mL/min/mm Hg. Figure 4–12 shows clinical conditions that may cause problems in diffusion. See Figure 4–8 for an illustration of the diffusion of oxygen during a diffusion-limited state. Table 4–3 presents factors that affect measured $D_{L_{CO}}$.

FIGURE 4–12 Clinical conditions that decrease the rate of gas diffusion. These conditions are known as *diffusion-limited problems.*

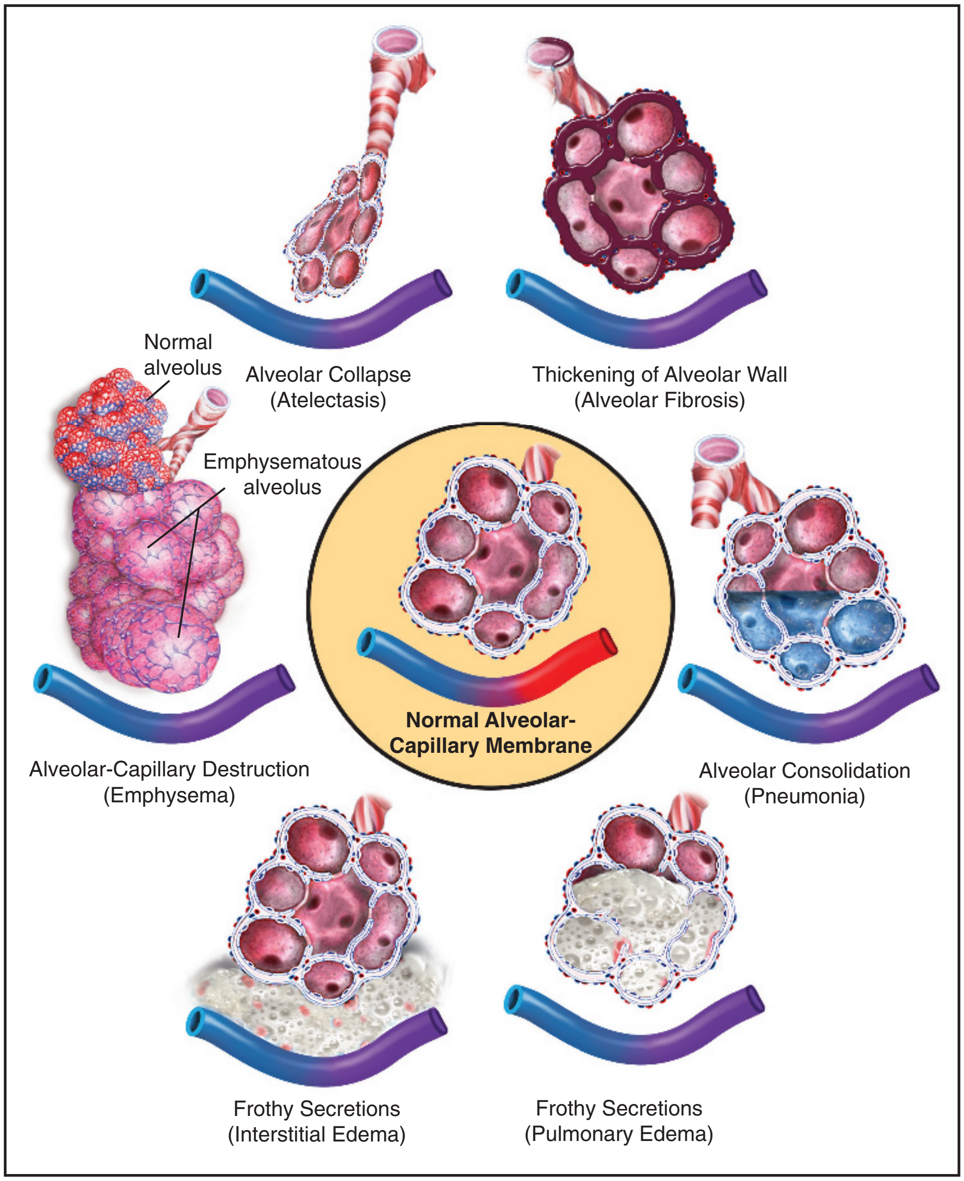

Alveolar Collapse
(Atelectasis)
Thickening of Alveolar Wall
(Alveolar Fibrosis)
Normal
alveolus
Emphysematous
alveolus
Normal Alveolar-
Capillary Membrane
Alveolar-Capillary Destruction
(Emphysema)
Alveolar Consolidation
(Pneumonia)
Frothy Secretions
(Interstitial Edema)
Frothy Secretions
(Pulmonary Edema)

TABLE 4-3 Factors That Affect Measured DL_{CO}

Age	The DL_{CO} progressively increases between birth and 20 years of age. After age 20, the DL_{CO} decreases as a result of the normal anatomic alterations of the lungs that reduce the overall alveolar-capillary surface area.
Lung volume	The DL_{CO} is directly related to an individual's lung size. Thus, the greater the subject's lung volume, the greater the DL_{CO}.
Body size	As a general rule, the DL_{CO} increases with body size. The size of the lungs is directly related to the subject's ideal body size. Thus, the larger the subject, the greater the lung size and the higher the DL_{CO}.
Body position	The DL_{CO} is about 15% to 20% greater when the individual is in the supine position, compared with the upright position.
Exercise	The DL_{CO} increases with exercise. This is most likely because of the increased cardiac output, and capillary recruitment and distention, associated with exercise.*
Alveolar P_{O_2} (PA_{O_2})	The DL_{CO} decreases in response to a high PA_{O_2}. This is because O_2 and Co both compete for the same hemoglobin sites.†
Hemoglobin concentration	*Anemia:* Patients with low hemoglobin content have a low CO-carrying capacity and, therefore, a low DL_{CO} value. *Polycythemia:* Patients with high hemoglobin content have a high CO-carrying capacity and, therefore, a high DL_{CO} value.
Carboxyhemoglobin	Individuals who already have CO bound to their hemoglobin (e.g., smokers or firefighters overcome by smoke inhalation) generate a "back pressure" to alveolar P_{CO}. This condition decreases the pressure gradient between the alveolar CO and the blood CO, which, in turn, reduces the DL_{CO} (see discussion of Fick's law).

* Refer to Chapter 5.
† Refer to Chapter 6.

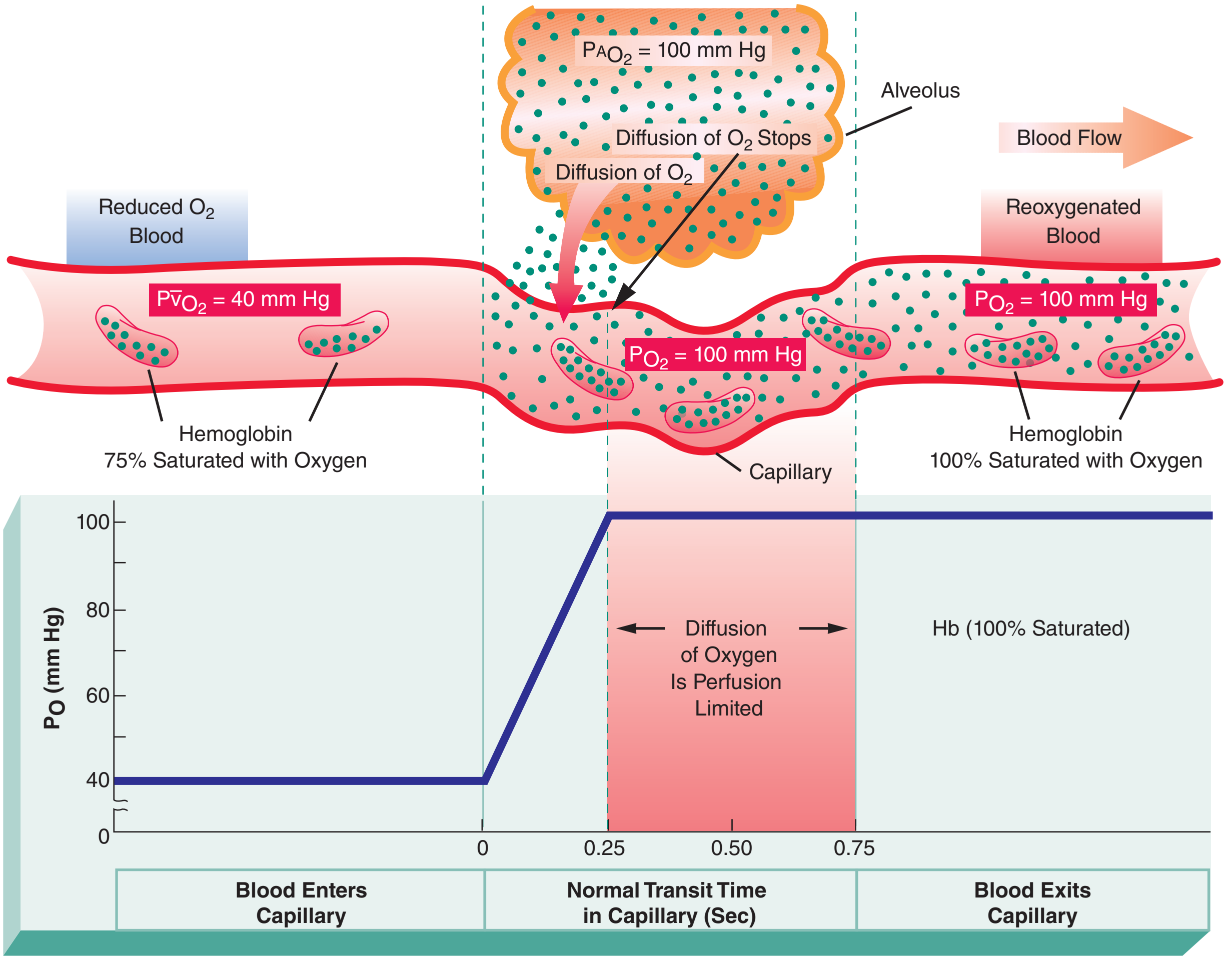
How Oxygen Can Be Either Perfusion or Diffusion Limited

When oxygen diffuses across the alveolar wall and into the blood, it enters the RBCs and combines with hemoglobin—but not with the same avidity as does carbon monoxide. Hemoglobin quickly becomes saturated with oxygen and, once this occurs, oxygen molecules in the plasma can no longer enter the RBCs. This, in turn, causes the partial pressure of oxygen in the plasma to increase.

Under normal resting conditions, the partial pressure of oxygen in the capillary blood equals the partial pressure of oxygen in the alveolar gas when the blood is about one-third of the way through the capillary. Beyond this point, the transfer of oxygen is perfusion limited (Figure 4–13). When the patient has either a decreased cardiac output or a decreased hemoglobin level (anemia), the effects of perfusion limitation may become significant.

When the diffusion properties of the lungs are impaired (see Figure 4–12), however, the partial pressure of oxygen in the capillary blood may never equal the partial pressure of the oxygen in the alveolar gas during the normal alveolar-capillary transit time. Thus, under normal circumstances the diffusion of oxygen is perfusion limited, but under certain abnormal pulmonary conditions the transfer of oxygen may become diffusion limited.

FIGURE 4-13 Under normal resting conditions, the diffusion of oxygen across the alveolar-capillary membrane stops when blood is about one-third of the way through the capillary. This occurs because the partial pressure of oxygen in the capillary blood (P_{O_2}) equals the partial pressure of oxygen in the alveolus (PA_{O_2}). Once oxygen equilibrium occurs between the alveolus and capillary blood, the diffusion of oxygen is *perfusion limited.*


PA_{O_2} = 100 mm Hg
Alveolus
Diffusion of O_2 Stops
Diffusion of O_2
Blood Flow
Reduced O_2 Blood
Reoxygenated Blood
$P\bar{v}O_2$ = 40 mm Hg
PO_2 = 100 mm Hg
PO_2 = 100 mm Hg
Hemoglobin 75% Saturated with Oxygen
Capillary
Hemoglobin 100% Saturated with Oxygen
PO (mm Hg)
100
80
60
40
0
Diffusion of Oxygen Is Perfusion Limited
Hb (100% Saturated)
0
0.25
0.50
0.75
Blood Enters Capillary
Normal Transit Time in Capillary (Sec)
Blood Exits Capillary

Clinical Connection 4-7

Why Nitrogen (or Argon) Gas Is Used as a Wine Preservative

Gases, such as nitrogen or argon, can be used to preserve a partial bottle of wine after it has been opened saving it for a later time (Figure 4–14). Because argon is expensive—and more difficult to obtain—nitrogen is the most commonly used gas to preserve a partially full bottle of wine after opening—with the hopes of preserving its flavor for future drinking. In general, the nitrogen is used to displace the oxygen in the bottle—in particular, the oxygen/liquid interface where the wine is in direct contact with the oxygen in the bottle (i.e., the oxygen directly above the wine). The nitrogen above the wine is commonly referred to as a blanketing barrier. By preventing the oxygen from interfacing with the wine, the oxidation of the wine is interrupted or slowed—thus, preserving the original taste of the wine.

Clinical Connection 4-7, Continued

FIGURE 4-14 Partially filled bottles of wine.

© Valentyn Volkov/Shutterstock.com.

Unfortunately, many merchants who promote various gas devices and gadgets for the preservation of wine often falsely claim—via their websites, brochures, advertising flyers, and YouTube promotions—that the gases they use (either nitrogen or argon) are actually "heavier" than oxygen and, therefore, will sink downward to the wine's surface and produce a protective blanket layer between the wine and the oxygen in the wine bottle. In essence, these wine accessory dealers are claiming that because nitrogen or argon is heavier than oxygen, the gas will create a protective barrier over the wine's surface—similar to the barrier created by oil that floats on top water because oil is lighter than water (Figure 4–15). Simply stated: **This is not true!**

FIGURE 4-15 Because water is heavier than oil, oil floats on top of water.

© Alireza Mehrfar/Shutterstock.com.

The reason these claims are false are as follows:

- First, and as the respiratory therapist readily knows, nitrogen and argon are gases—not liquids or solids. Based on kinetic theory, nitrogen and argon gas molecules are in constant, random motion. In addition, and like all gases, nitrogen and argon can easily be compressed or expand—because their respective molecules are far apart. Thus, due to their high kinetic energy, constant motion, and lack of mass, gases form homogeneous mixtures with each other—without exception (see Dalton's law, Figure 4–1).
- Second, consider the gram-molecular weight (GMW) of nitrogen and oxygen. It would be impossible for nitrogen to create a protective layer over the wine because it is "heavier." This is because the GMW of nitrogen is 28 and the GMW of oxygen is 32.[6] Thus, if nitrogen behaved according to its weight—**which it does not**—oxygen (being heavier than nitrogen) would actually create a layer over the surface of the wine, and the nitrogen would be forced to the top of the wine bottle. Again, this is not how it works.

How Nitrogen (Argon) Works to Preserve Wine[7]

Despite the misinformation described here, gases like nitrogen or argon can—**indeed**—preserve the life of a good wine. This is because preservation gas devices work differently than explained by the merchants in the preceding discussion.

In order to be effective, the wine preservation device must not just add nitrogen or argon to the wine bottle, but rather replace the oxygen in the bottle completely or substantially. By eliminating or greatly reducing the oxygen, the oxidation processes of the wine is interrupted, and the taste of the wine preserved.

There are several wine preservation devices available on the market today, and they basically work as follows:

1. Nitrogen (or argon) gases are available in pressurized cans with a hollow extension tube that can be inserted through the mouth of the wine bottle (Figure 4–16A).
2. The nitrogen (or argon) is injected into the wine bottle for a couple of seconds, which, in turn, forces all the oxygen out the top of the wine bottle (Figure 4–16B).

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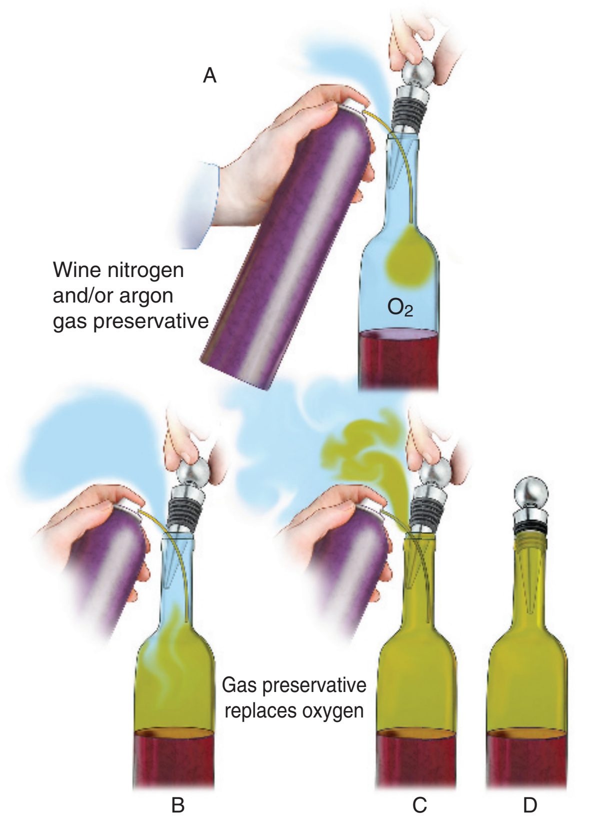
[6] The GMW of argon is 39.9.

[7] See Clinical Connection 6–7 for a similar discussion regarding misinformation.

Clinical Connection 4-7, Continued

FIGURE 4-16 **A.** The hollow extension tube attached to the pressurized wine gas preservative container is inserted through the mouth of the wine bottle. **B.** The gas preservative is injected into the wine bottle for a few seconds (green color). **C.** All the oxygen (blue color) is forced out of the top of the wine bottle—along with some gas preservative in this example. **D.** The top of the wine bottle is then sealed.


A
Wine nitrogen and/or argon gas preservative
O_2
Gas preservative replaces oxygen
B
C
D

3. The top of the wine bottle is then sealed (Figure 4–16C and Figure 4-16D) .
4. Even though the nitrogen (or argon) behaves like an ideal gas—that is, it expands to the limits of the bottle and generates its own partial pressure—the oxygen is forced out of the bottle by the pressurized nitrogen and the wine oxidation has been interrupted, thus preserving the bouquet of the wine. In fact, if done correctly, the only layer of gas above the wine's surface is nitrogen (or argon) behaving normally; that is, its molecules are in constant, random motion and fill the entire space throughout the upper portion of the wine bottle (see Figure 4–16D).

Caveat emptor—Let the buyer beware! When researching and purchasing any item, the buyer must always exercise caution in selecting an item that will actually function as intended—and, importantly, as advertised. Fortunately, in this case, injecting nitrogen or argon into partially filled bottles of wine actually does work—but not for the reasons touted by the many merchants who peddle them. As discussed, a thorough understanding of gas behavior—as well as its molecular and physical characteristics—provides the correct explanation. When used correctly, the nitrogen wine preservative canister will completely or substantially remove oxygen from a partially filled bottle of wine and, therefore, sustain its bouquet and taste. Cheers!

Finally, it should be noted that nitrogen is also widely used in other industries for protective purposes. For example, in food processing, nitrogen is commonly used to blanket edible oils, such as a bag of potato chips, to prevent staleness and rancidity.

Chapter Summary

Diffusion is the movement of gas molecules from an area of relatively high concentration of gas (high pressure) to one of low concentration (low pressure). When several different gases are mixed together, each gas in the mixture diffuses according to its own individual pressure gradient. Diffusion continues until all gases in the two areas are in equilibrium. Fundamental to the understanding of the diffusion of gases is Dalton's law. Dalton's law provides the basic foundation to understand (1) the gases that compose the barometric pressure, (2) the partial pressure of these gases in the air, alveoli, and blood, and (3) the ideal alveolar gas equation.

Essential to the knowledge base of gas diffusion is the understanding of (1) the diffusion of oxygen and carbon dioxide across the alveolar-capillary membrane; (2) Fick's law, including how Henry's law and Graham's law are used in Fick's law; (3) perfusion-limited gas flow; (4) diffusion-limited gas flow; and (5) how oxygen can be either perfusion or diffusion limited.

Clinical connections associated with these topics include (1) pulmonary disorders that increase the thickness of the alveolar-capillary thickness, (2) hyperbaric oxygen therapy—a clinical application of Henry's law, (3) oxygen toxicity, (4) clinical application of Fick's law, (5) respiratory disorders that reduce alveolar surface area, (6) decreased $D_{L_{CO}}$—the classic diagnostic sign of emphysema, and (7) why nitrogen (and argon) gas is used as a wine preservative.

1 Clinical Application Case

This 68-year-old man entered the hospital in severe left ventricular heart failure and pulmonary edema (Figure 4–17).[8] He appeared very anxious, and his lips and skin were blue. He had a frequent and strong cough, productive of moderate amounts of frothy, white, and pink secretions. The patient's vital signs were blood pressure—140/88 mm Hg, heart rate—93 beats/min and weak, and respiratory rate—28 breaths/min and shallow. On auscultation, crackles and rhonchi (fluid sounds) could be heard over both lung fields. His arterial oxygen pressure (Pa_{O_2}) was 53 mm Hg (normal range is 80 to 100 mm Hg).

The emergency department physician administered several different heart medications and a diuretic. The respiratory therapist placed a continuous positive airway pressure (CPAP) mask over the patient's nose and mouth and set the pressure at +10 cm H_2O and the fractional concentration of inspired oxygen (FI_{O_2}) at 0.4. One hour later, the patient was breathing comfortably. His lips and skin no longer appeared blue, and his cough was less frequent. No frothy or pink sputum was noted at this time. His vital signs were blood pressure—126/78 mm Hg, heart rate—77 beats/min, and respiratory rate—16 breaths/min. On auscultation, his breath sounds were improved. His arterial oxygen pressure (Pa_{O_2}) was 86 mm Hg.

Discussion

This case illustrates both the adverse and therapeutic effects of factors presented in Fick's law (see Figure 4–9). The patient presented in the emergency department in severe left ventricular heart failure and pulmonary edema (see Figure 4–17). This means that the patient's left ventricle was failing to pump blood adequately and caused blood to back up into the patient's lungs. This pathologic process, in turn, caused the patient's pulmonary blood pressure to increase. As the pulmonary blood pressure increased, fluid moved out of the pulmonary capillaries and into the extracapillary spaces, as well as into the alveoli and into the tracheobronchial tree. As a result of this process, the thickness of the alveolar-capillary membrane also increased (see Figure 4–4).

Because gas diffusion ($\dot{V}$) is *indirectly* related to thickness (T), the diffusion of oxygen across the alveolar-capillary membrane decreased (Fick's law). This fact was illustrated by the low Pa_{O_2} of 53 mm Hg when the patient first entered the hospital. The physician treated the original cause of this condition—the failing heart and fluid overload—with medications. As the cardiac function and fluid overload improved, the thickness of the alveolar-capillary membrane returned to normal. As the thickness of the alveolar-capillary membrane decreased, the diffusion of oxygen increased.

While the physician was treating the patient's failing heart, the respiratory therapist worked to offset the patient's poor oxygenation by increasing the patient's PA_{O_2} (P_1 of Fick's law). As Fick's law shows, the diffusion of gas is *directly* related to $P_1 - P_2$. The therapist increased the patient's PA_{O_2} by (1) increasing the pressure at the level of the patient's alveoli with the CPAP mask and (2) increasing the inspired FI_{O_2} to 0.4.

Thus, the reduction in alveolar-capillary membrane thickness (decreased via medications), the increased pressure at the level of the alveoli (produced via CPAP), and the increased FI_{O_2} (increased P_1) all worked to enhance the diffusion of oxygen, as shown by the Pa_{O_2} of 86 mm Hg achieved 1 hour later. The patient's cardiac condition progressively improved, and he was discharged from the hospital 2 days later.

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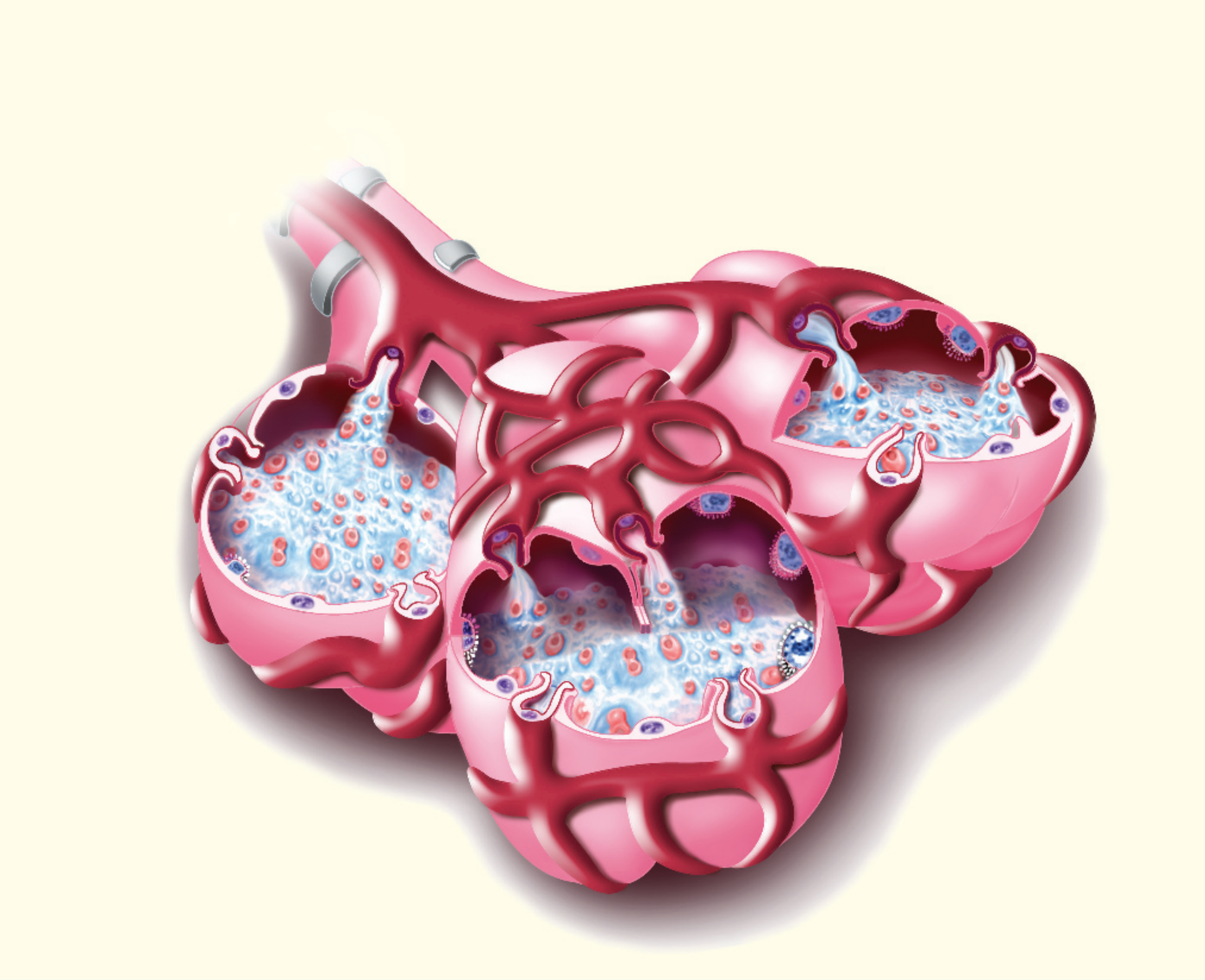
[8] Pulmonary edema refers to fluid accumulation in the alveoli and airways. Pulmonary edema is commonly associated with congestive heart failure (CHF).

Clinical Application Case 1 (continued)

FIGURE 4-17 Cross-sectional view of alveoli with pulmonary edema. Pathology includes (1) interstitial edema, (2) fluid engorgement throughout the alveolar wall interstitium, and (3) frothy white secretions in the alveoli.



2 Clinical Application Case

A 78-year-old woman with a long history of chronic interstitial lung disease (alveolar thickening and fibrosis) was admitted to the hospital because of respiratory distress. She was well known to the hospital staff. She had been admitted to the hospital on several occasions, and for the 2 years prior to this admission, she had been on continuous oxygen at home (2 L/min by nasal cannula). The home care respiratory therapist made regular visits to the patient's home to check on her equipment and to assess her respiratory status.

(*continued*)

Clinical Application Case 2 (continued)

In fact, it was the respiratory therapist who alerted the physician about the patient's poor respiratory status that prompted this hospitalization.

On admission, the patient appeared anxious and agitated. Her skin was pale and blue and felt cool and clammy. Her vital signs were blood pressure—166/91 mm Hg, heart rate—105 beats/min, and respiratory rate—24 breaths/min. Her breath sounds were clear and loud. Although chest X-ray regularly showed signs of increased alveolar density (white appearance) because of her lung fibrosis, this day's chest X-ray was markedly worse.

The physician on duty felt that the chest X-ray showed an acute inflammatory condition from an undetermined cause. The physician started the patient on corticosteroids. The respiratory therapist noted that even though the patient's alveolar oxygen pressure ($P_{A_{O_2}}$) was calculated to be 165 mm Hg, the patient's arterial oxygen pressure (Pa_{O_2}) was only 57 mm Hg (normal, 80 to 100 mm Hg). In response to the low Pa_{O_2}, the therapist increased the patient's inspired oxygen concentration $F_{I_{O_2}}$ from 2 L/min via nasal cannula (an $F_{I_{O_2}}$ of about 0.28) to 0.5 via an oxygen Venturi mask.

Over the next 24 hours, the patient's condition progressively improved. She stated that she was breathing much better. Her skin color returned to normal and no longer felt cold or wet. Her vital signs were blood pressure—128/86 mm Hg, heart rate—76 beats/min, and respiratory rate—14 breaths/min. A second chest X-ray showed improvement, compared with the previous day's chest X-ray, and her Pa_{O_2} was 89 mm Hg, within normal limits.

Discussion

This case illustrates both the acute and chronic effects of an increased alveolar-capillary membrane. As Fick's law states, the diffusion of gas is *indirectly* related to the thickness of the alveolar-capillary membrane, and *directly* related to $P_1 - P_2$ (see Figure 4–8). Because the patient had chronic alveolar fibrosis and thickening, her oxygen diffusion was low. This is why continuous oxygen (2 L/min) administered via nasal cannula at home was needed to offset this condition. Increasing the alveolar oxygen level (i.e., increasing the $P_{A_{O_2}}$ or P_1) enhanced oxygen diffusion. When the patient's usual chronic status was stable, the 2 L/min oxygen via cannula at home was usually adequate to oxygenate her alveolar-capillary blood.

Because the patient had an acute alveolar inflammatory condition overlying her chronic problem, her alveolar-capillary membrane became even thicker. As a result, her usual home oxygen administration was not enough to meet the new challenge. Over the course of her hospitalization, however, the steroid therapy reduced her alveolar inflammation. As the acute alveolar inflammation improved, the thickness of her alveolar-capillary membrane decreased. While this process was taking place, the increased oxygen concentration (P_1) worked to offset the patient's poor oxygenation status and thus worked to make her comfortable. The patient continued to improve and was discharged on day 5 of her hospital stay. She continued to use oxygen via nasal cannula at home.

Review Questions

1. Assuming a normal barometric pressure of 760 mm Hg, if the percentage of oxygen is 0.4, the partial pressure of oxygen would be:

A. 159 mm Hg
B. 215 mm Hg
C. 304 mm Hg
D. 560 mm Hg

2. How many feet below sea level must an individual descend to exert a total pressure on the body of 3 atmospheres (2280 mm Hg)?

A. 13 feet
B. 33 feet
C. 66 feet
D. 99 feet

3. Which of the following gas laws states that in a mixture of gases the total pressure is equal to the sum of the partial pressure of each gas?

A. Dalton's law
B. Gay-Lussac's law
C. Charles' law
D. Boyle's law

4. At sea level, the normal percentage of carbon dioxide (CO_2) in the atmosphere is

A. 5%
B. 40%
C. 78%
D. 0.03%

5. At sea level, the alveolar water vapor pressure is normally about

A. 0.2 mm Hg
B. 47 mm Hg
C. 0.0 mm Hg
D. 40 mm Hg

6. If a patient is receiving an FI_{O_2} of 0.60 on a day when the barometric pressure is 725 mm Hg, and if the Pa_{CO_2} is 50 mm Hg, what is the patient's alveolar oxygen tension (PA_{O_2})?

A. 177 mm Hg
B. 233 mm Hg
C. 344 mm Hg
D. 415 mm Hg

7. The normal transit time for blood through the alveolar-capillary system is about

A. 0.25 second
B. 0.50 second
C. 0.75 second
D. 1.0 second

8. Under normal resting conditions, the diffusion of oxygen and carbon dioxide is usually completed in about

1. 0.25 second
2. 0.50 second
3. 0.75 second
4. 1.0 second
5. one-third of the time available:

A. 2 only
B. 3 only
C. 4 and 5 only
D. 1 and 5 only

9. Which of the following states that the rate of gas diffusion is inversely proportional to the weight of the gas?

A. Graham's law
B. Charles' law
C. Henry's law
D. Gay-Lussac's law

10. According to Fick's law, gas diffusion is

1. Directly proportional to the thickness of the tissue
2. Indirectly proportional to the diffusion constants
3. Directly proportional to the difference in partial pressure of the gas between the two sides
4. Indirectly proportional to the tissue area

A. 1 only
B. 3 only
C. 4 only
D. 2 and 3 only

Clinical Application Questions

Case 1

1. As a result of the severe left heart failure and increased pulmonary blood pressure in the case, fluid moved out of the pulmonary capillaries and into the extracapillary spaces. The pathologic process caused the thickness of the alveolar-capillary membrane to __________ __________________________________.

2. Because gas diffusion is indirectly related to the thickness, the diffusion of oxygen across the alveolar-capillary membrane in this case __________________________________.

3. While the physician was treating the patient's failing heart, the respiratory therapist worked to offset the patient's poor oxygenation by increasing the patient's __________, which is __________ of Fick's law.

4. The therapist achieved the goal in question 3 by increasing the patient's overall __________ __________________________________, and increasing the inspired ________________ ______________________________.

Case 2

1. Which factor in Fick's law confirmed why the patient's oxygenation status was chronically low in this case?

____

2. Which factor in Fick's law was used therapeutically to improve the patient's oxygenation status?

____

3. Which factor in Fick's law caused the patient's oxygenation status to acutely worsen in this case?

____

4. In addition to the corticosteroid therapy, what factor in Fick's law was used therapeutically to improve the patient's oxygenation status?

____

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CHAPTER 5

The Anatomy and Physiology of the Circulatory System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the function of the following specialized cells (formed elements) in the plasma: red blood cells (erythrocytes), white blood cells (leukocytes), and platelets (thrombocytes).
2. List the chemical components of plasma.
3. Describe the structure and function of the components of the heart.
4. Describe the function of the major components of the pericardium.
5. Describe the major components of the heart wall.
6. Describe the blood supply of the heart.
7. Describe how blood flows through the heart.
8. Describe the components of the pulmonary and systemic vascular systems.
9. Explain the neural control of the vascular system.
10. Describe the function of the baroreceptors.
11. Differentiate between the following types of pressures: intravascular pressure, transmural pressure, and driving pressure.
12. Describe how ventricular systole and ventricular diastole relate to the cardiac cycle and blood pressure.
13. List the intraluminal blood pressures throughout the pulmonary and systemic vascular systems.
14. Describe how blood volume affects blood pressure.
15. Identify the percentage of blood found throughout the various parts of the pulmonary and systemic systems.
16. Describe the influence of gravity on blood flow.
17. Define the determinants of cardiac output.
18. Define *vascular resistance.*

Introduction

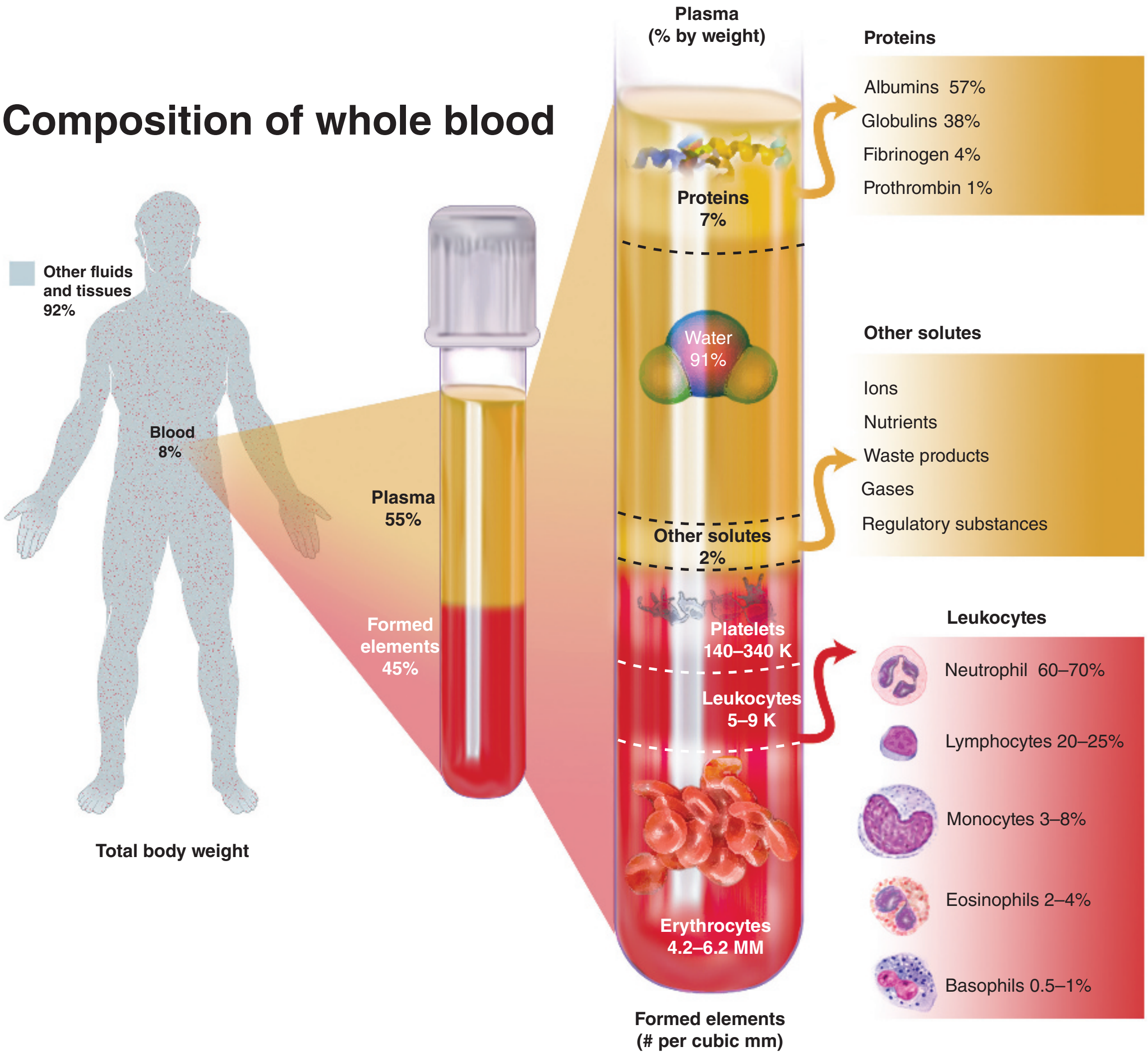
The transport of oxygen from the lungs to the cells of the body and the transport of carbon dioxide from the tissue cells to the lungs are a function of blood flow. Thus, when the flow of blood is inadequate, good alveolar ventilation is of little value. The circulatory system consists of the **blood**, the **heart** (pump), and the **vascular system**.

The Blood

As shown in Figure 5–1, whole **blood** consists of a variety of specialized cells, called **formed elements**, which are suspended in a liquid matrix called **plasma**. Blood makes up about 8 percent of the total body weight. The average total blood volume in the adult male is about 5 to 6 L and about 4 to 5 L in the adult female. The *formed elements* make up about 45 percent, and the plasma makes up about 55 percent of the total blood volume. The formed elements are composed of the **red blood cells**, the **white blood cells** (neutrophils, lymphocytes, monocytes, eosinophils, and basophils), and **platelets**. The *plasma* is composed of about 91 percent water, 7 percent proteins (albumins, globulins, and fibrinogen), and 2 percent other substances (electrolytes, nutrients, respiratory gases, waste products, and regulatory substances).

The functions of blood are to (1) transport oxygen to the tissue cells and carbon dioxide to the lungs; (2) transport nutrients and waste products; (3) transport processed molecules from one part of the body to another—for example, lactic acid is carried by the blood to the liver, where it is converted into glucose; (4) transport regulatory hormones and enzymes; (5) regulate the pH and osmosis; (6) maintain body temperature; (7) protect against foreign substance; and (8) form clots.

FIGURE 5-1 Composition of whole blood.


Composition of whole blood
Other fluids and tissues 92%
Blood 8%
Total body weight
Plasma 55%
Formed elements 45%
Plasma (% by weight)
Proteins 7%
Water 91%
Other solutes 2%
Platelets 140–340 K
Leukocytes 5–9 K
Erythrocytes 4.2–6.2 MM
Formed elements (# per cubic mm)
Proteins
Albumins 57%
Globulins 38%
Fibrinogen 4%
Prothrombin 1%
Other solutes
Ions
Nutrients
Waste products
Gases
Regulatory substances
Leukocytes
Neutrophil 60–70%
Lymphocytes 20–25%
Monocytes 3–8%
Eosinophils 2–4%
Basophils 0.5–1%

Red Blood Cells (Erythrocytes)

The primary function of **red blood cells (RBCs)**, or **erythrocytes**, is to transport oxygen from the lungs to the tissues and to transport carbon dioxide from the tissue cells to the lungs. In the normal adult, the number of RBCs ranges between 4.2 and 6.2 million per cubic millimeter of blood (mm^3). The average RBC count for the adult male is about 5.8 million per mm^3, and for adult female about 4.8 million per mm^3. The percentage of RBCs in relation to the total blood volume is known as the **hematocrit**. In the normal adult male, the hematocrit is about 45 percent, and about 42 percent in the normal adult female. In the healthy newborn, the hematocrit ranges between 45 and 60 percent.

Microscopically, the RBCs appear as biconcave discs, averaging about 7.5 μm in diameter and 2.5 μm in thickness, with the edges that are thicker than the center of the cell. The biconcave shape increases the surface area of the RBC compared to a flat shaped disc of the same size. The greater surface area enhances the movement of gases into and out of the RBC. The RBCs are produced in the red bone marrow in the spongy bone of the cranium, bodies of vertebrae, ribs, sternum, and proximal epiphyses of the humerus and femur. It is estimated that the RBCs are produced at the rate of 2 million cells per second. An equal number of worn-out RBCs are destroyed each second by the spleen and liver. The life span of a RBC is about 120 days.

The major substance of the RBCs is **hemoglobin**, which occupies about one-third of the cells' volume and accounts for its red color. The primary functions of hemoglobin are to transport oxygen from the lungs to the tissue cells, and to transport carbon dioxide from the tissue cells to the lungs.[1]

White Blood Cells (Leukocytes)

The **white blood cells (WBCs)**, or **leukocytes**, protect the body against invading microorganism—for example, bacteria, viruses, parasites, toxins, and tumors—and work to remove dead cells and debris from the body. There are five different types of WBCs, which are classified as either *granulocytes* or *agranulocytes,* according to (1) the presence or absence of granules and (2) the staining characteristics of their cytoplasm.

Granulocytes include the following three WBCs—named according to their cytoplasmic staining properties—that have large granules embedded in their cytoplasm:

- Neutrophils
- Eosinophils
- Basophils

Agranulocytes include the following two WBCs—leukocytes without cytoplasmic granules:

- Lymphocytes
- Monocytes

Unlike the red blood cells, which are confined to the blood vessels, the WBCs are able to leave the blood vessels—a process called **diapedesis**—when needed for inflammatory or immune responses. Diapedesis is activated by chemical signals released by the damaged cells **(positive chemotaxis)**. Once the WBCs are out of the blood stream, they form cytoplasmic extensions that are used to migrate through the tissue spaces toward the damaged cells. This unique WBC motility is called **ameboid movement**.

The normal average number of WBCs ranges between 5000 and 9000 cells/mm^3. An overall increase in the number of WBCs is called **leukocytosis**. An overall decrease in the number of WBCs is called **leukopenia**. A patient's WBC count is obtained from the **differential WBC count**, which is a component of one of the most useful and frequently performed diagnostic blood test called the **complete blood cell count**, or

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[1] The role of hemoglobin in the transport of oxygen and carbon dioxide is discussed in detail in Chapter 6.

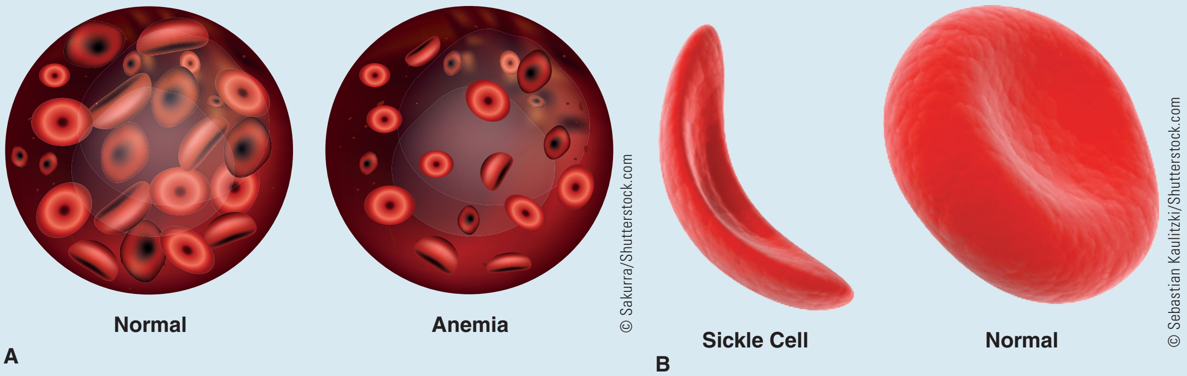
Clinical Connection 5-1

Anemia

Anemia is defined as a deficiency of hemoglobin in the blood (Figure 5–2A). It can be caused by a reduced number of red blood cells, a decrease in the amount of hemoglobin in each red blood cell, or both. A decreased hemoglobin level decreases the ability of blood to transport oxygen. Common causes of anemia include:

- **Nutritional deficiency (iron deficiency anemia)** is caused by a reduced intake or absorption of iron. This form of anemia results in a reduced hemoglobin production and smaller red blood cells (microcytic).
- **Hemorrhagic anemia** is caused by a blood loss, such as can result from trauma, ulcers, or excessive menstrual bleeding. Chronic blood loss, in which small amounts of blood are lost over a period of time, can also cause iron-deficiency anemia.
- **Folate deficiency**—an inadequate intake of folate in the diet—can cause anemia. Common sources of folate include brewer's yeast, lentils, romaine lettuce, pinto beans, okra, black beans, black-eye peas, spinach, and kidney beans. Folate deficiency is commonly seen in pregnant women, the poor, and chronic alcoholics.
- **Pernicious anemia** is caused by an inadequate dietary intake of vitamin B_{12}. Vitamin B_{12} is important for folate synthesis. A vitamin B_{12} deficiency causes a secondary folate deficiency. Thus, a vitamin B_{12} deficiency also causes a decreased production of red blood cells that are larger than normal.
- **Hemolytic anemia** can develop when the red blood cells rupture or are destroyed at an excessive rate. Causes of hemolytic anemia include inherited defects within the red blood cells, drugs, snake venom, artificial heart valves, autoimmune disease, or hemolytic disease of the newborn.
- **Aplastic anemia** is caused by the inability of the bone marrow to produce red blood cells. Causes of aplastic anemia include chemicals (e.g., benzene), drugs (e.g., certain antibiotics and sedatives), or radiation.
- **Sickle-cell anemia** is an autosomal recessive hereditary disorder found mostly in people of African ancestry, and occasionally among people of Mediterranean heritage. The hemoglobin in a person with sickle-cell anemia causes the red blood cells to become sickle-shaped and rigid—resulting in plugging of small blood vessels (Figure 5–2B). They are also more fragile than normal red blood cells. In severe cases, sickle-cell anemia is usually fatal before the person is 30 years of age.

FIGURE 5-2 **A.** Normal and anemia. **B.** Sickle cell anemia and normal.



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simply the **CBC** (see Clinical Connection 5–2: Complete Blood Cell Count). In a differential WBC count, the proportions of each type of white blood cell are reported as percentages of the total WBC count. Because these numbers change certain abnormal conditions, they have clinical significance. For example, during an asthmatic episode, the percentage of eosinophils is elevated. Table 5–1 provides the WBC percentages.

TABLE 5-1 Differential Count of White Blood Cells*

Class	Normal Range (%)	Typical Value (%)**
Neutrophils	65–75	65
Lymphocytes	20–25	25
Monocytes	3–8	6
Eosinophils	2–5	3
Basophils	0.5–1	1
Total	100	100

*The sum of the percentage of any differential count must, of course, always be 100%.

A good mnemonic phrase to help remember percent values in decreasing order is the following: "N**ever **L**et **M**onkeys **E**at **B**ananas."

Granulocytes

Neutrophils. **Neutrophils** contain cytoplasmic granules that are numerous. Because the nuclei of the neutrophils have two, three, or more lobes, they are also called **polymorphonuclear leukocytes**. Under normal conditions, the neutrophil numbers average about 65 percent of the total WBC count. The neutrophils are very mobile, active phagocytic cells. The cytoplasmic granules in the neutrophils contain powerful lysosomes, which are digestivelike enzymes that phagocytize invading bacteria.

Eosinophils. **Eosinophils** contain cytoplasmic granules that are large, numerous, and coarse in appearance. The cytoplasmic granules stain orange-red. Their nuclei usually have two lobes. Normally, the eosinophils make up about 2 to 5 percent of the circulating WBCs. The eosinophils are numerous in the tissue lining the respiratory and digestive tracts. Eosinophils destroy protozoa and parasitic worms, and release anti-inflammatory substances in antigen–antibody reactions. An elevated eosinophil count is commonly seen in asthmatic patients.

Clinical Connection 5-2

Complete Blood Cell Count

The **complete blood cell count (CBC)** is one of the most useful and frequently ordered blood tests (Figure 5–3). The CBC consists of a battery of tests that measures the patient's standard red blood cell, white blood cell, and thrombocyte counts; the differential white blood cell count; hematocrit; hemoglobin content; and other characteristics of the formed blood elements. The respiratory therapist often reviews the patient's CBC when assessing the patient's red blood cell count, differential white blood cell count, hematocrit, and hemoglobin level.

FIGURE 5-3 Complete blood cell count.

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Basophils. **Basophils** are the least numerous of the WBCs, accounting for 0.5 to 1 percent of the total WBC count. The cytoplasmic granules are sparse, relatively large, and stain blue to dark purple. The nuclei of the basophils appear S-shaped and the cytoplasmic granules contain **histamine** and **heparin**. *Histamine* is an inflammatory substance that causes vasodilation and attracts other WBCs to the inflamed site. The *heparin* inhibits blood clotting (an anticoagulant). The basophils increase in number in both allergic and inflammatory reactions.

Agranulocytes

Lymphocytes. **Lymphocytes** are the second most numerous leukocytes in the blood, accounting for 25 percent of the total WBC count. The lymphocytes stain dark purple and their nuclei are usually spherical in shape and surrounded by a thin rim of pale blue cytoplasm. Although large numbers of lymphocytes exist in the body, only a small amount is found in the bloodstream. Most of the lymphocytes are found in the lymphoid tissues (lymph nodes), where they play a number of important roles in immunity. For example, the **T lymphocytes** (T cells) function in the immune response by acting directly against virus-infected cells and tumors. **B lymphocytes** (B cells) give rise to *plasma cells,* which produce **antibodies** (immunoglobulins) that work to inactivate invading antigens.

Monocytes. **Monocytes** are the largest of the WBCs and account for 4 to 8 percent of the WBCs. They have pale blue cytoplasm and a darkly stained U-shaped or kidney-shaped nucleus. In the tissue, monocytes differentiate into highly mobile **macrophages** with large appetites. They phagocytize bacteria, dead cells, cell fragments, and viral-infected cells. An increase in the number of monocytes is associated with chronic infections, such as tuberculosis.

Platelets

Platelets, or **thrombocytes**, are the smallest of the formed elements in the plasma. Platelets are roughly disk-shaped and average about 3 µm in diameter. The normal platelet count ranges from 250,000 to 500,000/mm^3 of blood. The platelets play an important role in preventing blood loss from a traumatized area by (1) forming platelet plugs that seal holes in small blood vessels and (2) forming blood clots, which work to seal off larger tears in the blood vessels. The platelets also contain *serotonin,* which, when released, causes smooth-muscle constriction and reduced blood flow.

Table 5–2 summarizes the formed elements of the blood.

Plasma

Plasma is the liquid part of the blood—whole blood without the formed elements. Plasma constitutes about 55 percent of the total blood volume (see Figure 5–1). Plasma is a pale yellow fluid that consists of about 91 percent water and 7 percent proteins (albumins, globulins, fibrinogen, and prothrombin) with other solutes (electrolytes, nutrients, respiratory, gases, waste products, and regulatory substances). Table 5–3 outlines the chemical composition of plasma.

The Heart

The **heart** is a hollow, four-chambered, muscular organ that consists of the upper right and left **atria** and the lower right and left **ventricles** (Figure 5–4). The atria are separated by a thin muscular wall called the **interatrial septum**; the ventricles are separated by a thick muscular wall called the **interventricular septum**. The heart actually functions as two separate pumps. The right atrium and ventricle act as one pump to propel unoxygenated blood to the lungs. At the same time, the left atrium and ventricle act as

TABLE 5-2 Formed Elements of the Blood

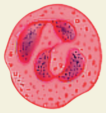
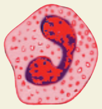
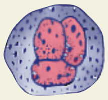
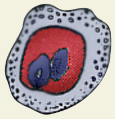
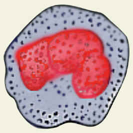
Cell Type	Illustration	Description	Number of Cells/mm^3 of Blood	Duration of Development (D) and Life Span (LS)	Function
Erythrocytes (red blood cells [RBCs])		Biconcave, anucleate disc; salmon-colored; diameter 7–8 μm	4–6 million	D: 5–7 days LS: 100–120 days	Transport oxygen and carbon dioxide
Leukocytes (white blood cells [WBCs])		Spherical, nucleated cells	4,000–11,000		
Neutrophils		Nucleus multilobed; inconspicuous cytoplasmic granules; diameter 10–14 μm	3000–7000	D: 6–9 days LS: 6 hours to a few days	Phagocytize bacteria
Eosinophils		Nucleus bilobed; red cytoplasmic granules; diameter 10–14 μm	100–400	D: 6–9 days LS: 8–12 days	Kill parasitic worms; destroy antigen–antibody complexes; inactivate some inflammatory chemicals of allergy
Basophils		Nucleus lobed; large blue-purple cytoplasmic granules; diameter 10–12 μm	20–50	D: 3–7 days LS: a few hours to a few days	Release histamine and other mediators of inflammation; contain heparin, an anticoagulant
Agranulocytes Lymphocytes		Nucleus spherical or indented; pale blue cytoplasm; diameter 5–17 μm	1500–3000	D: days to weeks LS: hours to years	Mount immune response by direct cell attack or via antibodies
Monocytes		Nucleus, U or kidney-shaped; gray-blue cytoplasm; diameter 14–24 μm	100–700	D: 2–3 days LS: months	Phagocytosis; develop into macrophages in tissues
Platelets		Discoid cytoplasmic fragments containing granules; stain deep purple; diameter 2–4 μm	250,000–500,000	D: 4–5 days LS: 5–10 days	Seal small tears in blood vessels; instrumental in blood clotting

TABLE 5-3 Chemical Composition of Plasma

Water		**Food Substances**	
	93% of plasma weight	Amino acids	40 mg/100 mL
Proteins		Glucose/carbohydrates	100 mg/100 mL
Albumins	4.5 g/100 mL	Lipids	500 mg/100 mL
Globulins	2.5 g/100 mL	Individual vitamins	0.0001–2.5 mg/100 mL
Fibrinogen	0.3 g/100 mL		
Prothrombin	<0.1 g/100 mL	**Respiratory Gases**	
		O_2	0.3 mL/100 mL
Electrolytes		CO_2	2 mL/100 mL
Cations		N_2	0.9 mL/100 mL
Na^+	143 mEq/L		
K^+	4 mEq/L	**Individual Hormones**	
Ca^{2+}	2.5 mEq/L		0.000001–0.05 mg/100 mL
Mg^{2+}	1.5 mEq/L		
Anions		**Waste Products**	
Cl^-	103 mEq/L	Urea	34 mg/100 mL
PO_4^{3-}	1 mEq/L	Creatinine	1 mg/100 mL
SO_4^{2-}	0.5 mEq/L	Uric acid	5 mg/100 mL
HCO_3^-	27 mEq/L	Bilirubin	0.2–1.2 mg/100 mL

another pump to propel oxygenated blood throughout the systemic circulation. Compared with the ventricles, the atria are small, thin-walled chambers. As a rule, they contribute little to the propulsive pumping activity of the heart.

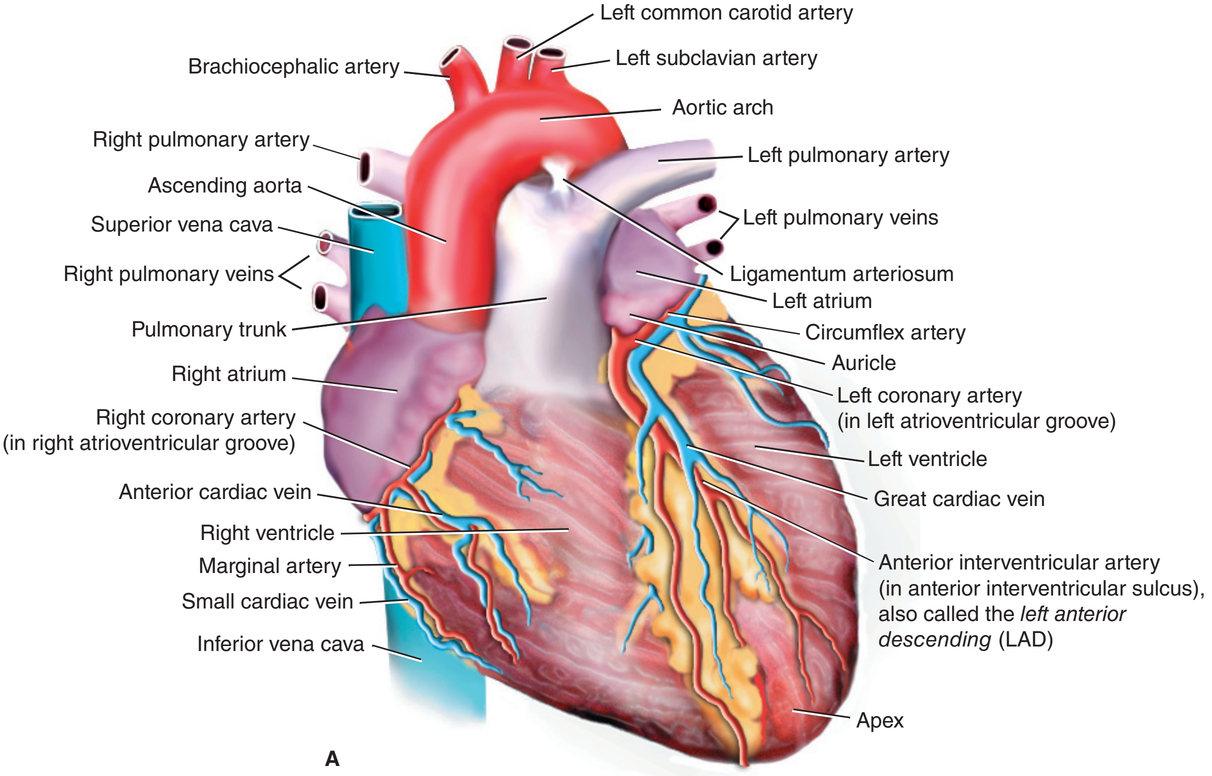
Externally, the heart appears as a cone-shaped structure, weighing between 250 and 350 g. It is enclosed in the **mediastinum** and extends obliquely between the second rib and the fifth intercostal space (Figure 5–5A). The heart rests on the superior surface of the diaphragm, anterior to the vertebral column and posterior to the sternum (Figure 5–5B). Both the left and right lateral portions of the heart are flanked by the lungs, which partially obscure it (Figure 5–5C). Approximately two-thirds of the heart lies to the left of the midsternal line; the balance extends to the right.

The **base** of the heart is broad and flat, about 9 cm, and points toward the right shoulder. The **apex** points inferiorly toward the left hip. When fingers are pressed between the fifth and sixth ribs just below the left nipple, the heart beat can be felt where the apex is in contact with the internal chest wall. This site is called the **point of maximal intensity (PMI)**.

The Pericardium

The heart is enclosed in a double-walled sac called the **pericardium** (Figure 5–6). The outer wall, the **fibrous pericardium**, is a tough, dense, connective tissue layer. Its primary function is to (1) protect the heart; (2) anchor the heart to surrounding structures, such as the diaphragm and the great vessels; and (3) prevent the heart from overfilling. The inner wall, the **serous pericardium**, is a thin, slippery, serous membrane. The serous pericardium is composed of two layers: the **parietal layer**, which lines the internal surface of the fibrous pericardium, and the **visceral layer** (also called the **epicardium)**. The epicardium is an integral part of the heart often described as the outermost layer of the heart. Between the two layers of the serous pericardium there is a film of serous fluid, which allows the parietal and visceral membranes to glide smoothly against one another, which in turn permits the heart to work in a relatively friction-free environment.

FIGURE 5-4 **A.** Anterior view of the heart. **B.** Posterior view of the heart.


Left common carotid artery
Brachiocephalic artery
Left subclavian artery
Aortic arch
Right pulmonary artery
Left pulmonary artery
Ascending aorta
Superior vena cava
Left pulmonary veins
Right pulmonary veins
Ligamentum arteriosum
Left atrium
Pulmonary trunk
Circumflex artery
Auricle
Right atrium
Left coronary artery
(in left atrioventricular groove)
Right coronary artery
(in right atrioventricular groove)
Left ventricle
Great cardiac vein
Anterior cardiac vein
Right ventricle
Marginal artery
Anterior interventricular artery
(in anterior interventricular sulcus),
also called the *left anterior descending* (LAD)
Small cardiac vein
Inferior vena cava
Apex
A

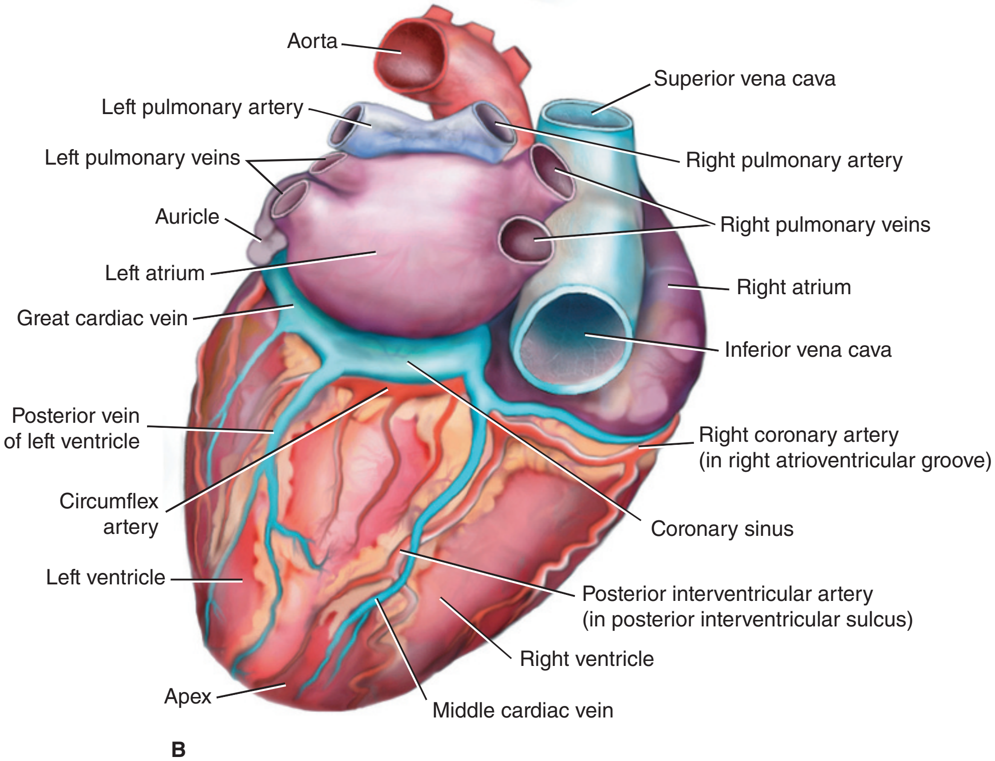

Aorta
Superior vena cava
Left pulmonary artery
Right pulmonary artery
Left pulmonary veins
Auricle
Right pulmonary veins
Left atrium
Right atrium
Great cardiac vein
Inferior vena cava
Posterior vein
of left ventricle
Right coronary artery
(in right atrioventricular groove)
Circumflex
artery
Coronary sinus
Left ventricle
Posterior interventricular artery
(in posterior interventricular sulcus)
Right ventricle
Apex
Middle cardiac vein
B

FIGURE 5-5 The relationship of the heart to the thorax: **(A)** the relationship of the heart to the sternum, ribs, and diaphragm; **(B)** a cross-sectional view showing the relationship of the heart to the thorax; **(C)** the relationship of the heart to the lungs and great vessels.

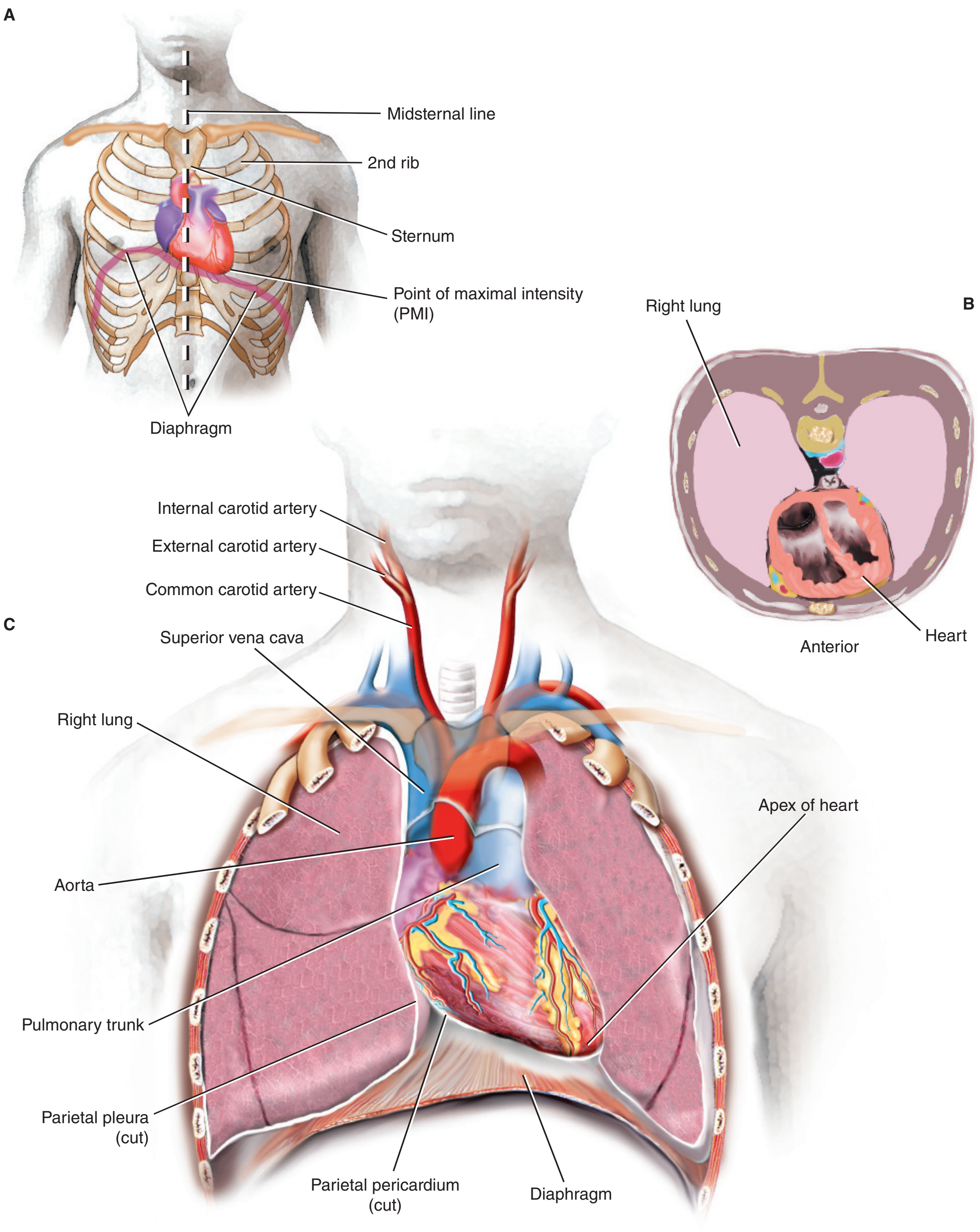
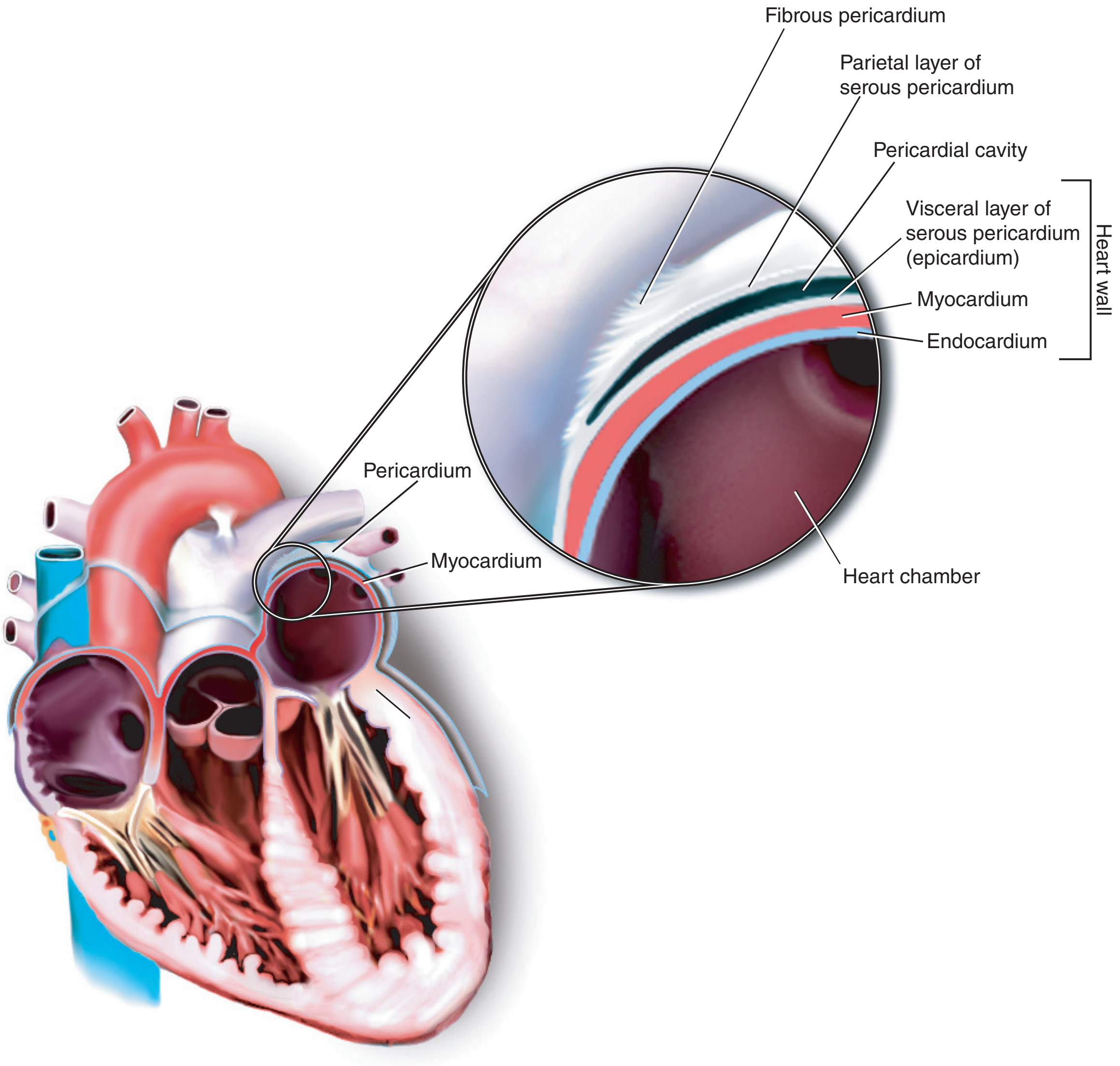

A
Midsternal line
2nd rib
Sternum
Point of maximal intensity (PMI)
Diaphragm
Right lung
B
Anterior
Heart
Internal carotid artery
External carotid artery
Common carotid artery
C
Superior vena cava
Right lung
Apex of heart
Aorta
Pulmonary trunk
Parietal pleura (cut)
Parietal pericardium (cut)
Diaphragm

FIGURE 5-6 The layers of the pericardium and the heart wall.


Fibrous pericardium
Parietal layer of serous pericardium
Pericardial cavity
Visceral layer of serous pericardium (epicardium)
Myocardium
Endocardium
Heart wall
Pericardium
Myocardium
Heart chamber

Clinical Connection 5-3

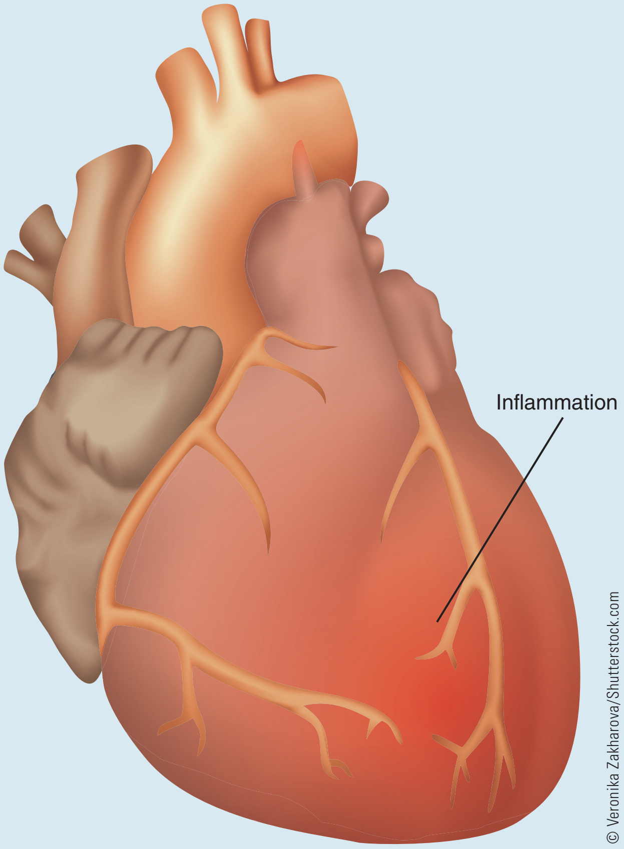
Pericarditis

Pericarditis is an inflammation of the pericardium, the fibroserous sac enclosing the heart and the roots of the great vessels (Figures 5–6 and 5–7). Although the cause is often unknown, it is associated with trauma, infection, myocardial infarction, and malignant neoplastic disease. Pericarditis can be extremely painful, with sensations radiating between the patient's back and chest—sometimes being confused with the pain of myocardial infarction (heart attack). Pericarditis can result in excessive fluid accumulation within the pericardial sac—a **cardiac tamponade** (see Clinical Connection 5–4: Cardiac Tamponade).

(*Continued*)

Clinical Connection 5-3, Continued

FIGURE 5-7 Pericarditis—the inflammation of the pericardium.



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Clinical Connection 5-4

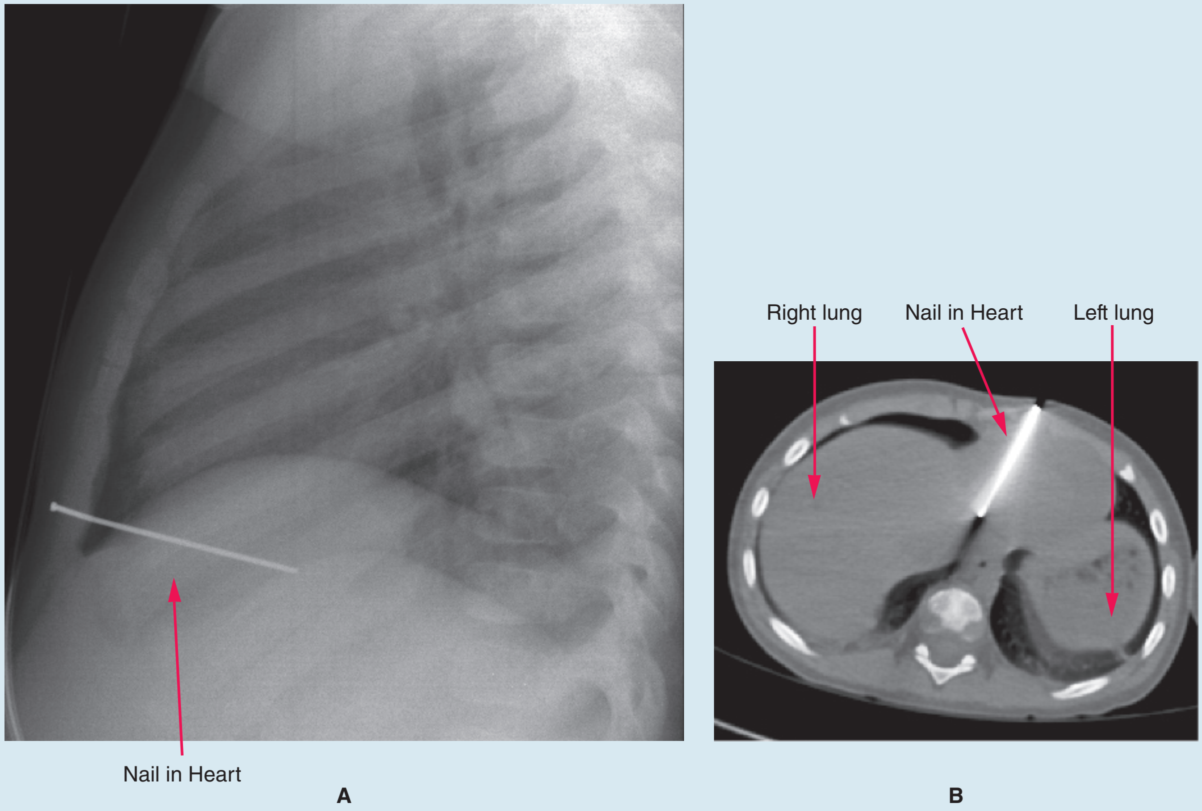
Cardiac Tamponade

A **cardiac tamponade** (also called cardiac compression or pericardial tamponade) is a potential medical emergency in which a large volume of fluid or blood collects in the pericardial sac. Because the fluid compresses the heart from the outside, the heart cannot adequately fill with blood during relaxation (diastole). Consequently, the patient's cardiac output and blood pressure rapidly decrease, causing the patient to die. Causes of a cardiac tamponade include trauma, rupture of the heart wall following a myocardial infarction, rupture of blood vessels caused by a malignant tumor, and radiation therapy. Treatment includes the insertion of a needle into the pericardial cavity and a syringe to drain the fluid.

Figure 5–8 shows the chest X-ray and CT scan of a 2-year-old boy who developed a cardiac tamponade after being accidently shot in right ventricle by his 4-year-old sister with their father's nail gun—and lived to tell about it!

Clinical Connection 5-4, Continued

FIGURE 5-8 The chest X-ray and CT scan of a 2-year-old boy who developed a cardiac tamponade. **A.** Nail in a lateral chest X-ray. **B.** CT scan showing the nail lodged in the right ventricle.



Courtesy T. Des Jardins, WindMist LLC

Courtesy T. Des Jardins, WindMist LLC

The Wall of the Heart

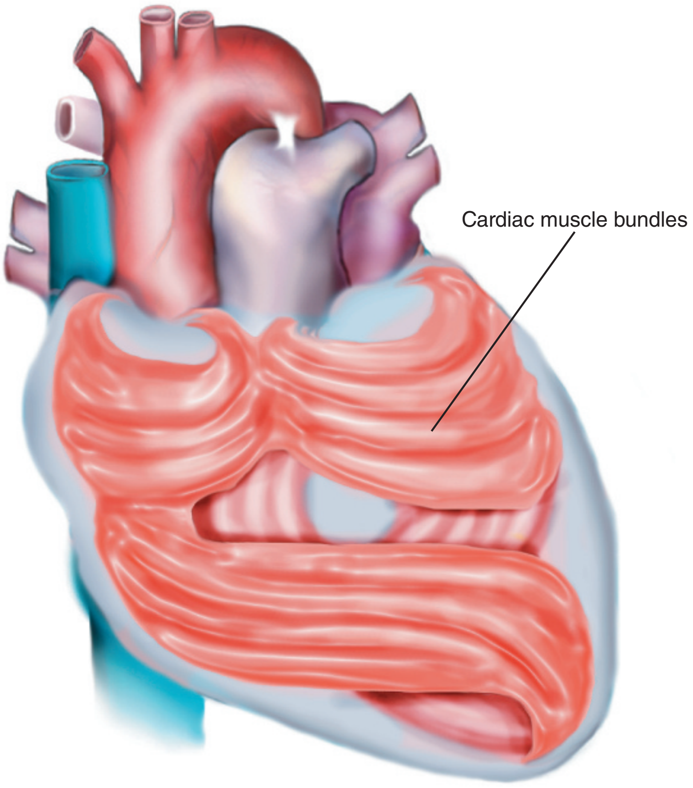
The heart wall is composed of the following three layers: epicardium (visceral pericardium), myocardium, and endocardium (see Figure 5–6).

The **epicardium**, or visceral layer of the pericardium, is composed of a single sheet of squamous epithelial cells overlying delicate connective tissue. In older patients, the epicardium layer is often infiltrated with fat.

The **myocardium** is a thick contractile middle layer of uniquely constructed and arranged muscle cells. The myocardium forms the bulk of the heart. It is the layer that actually contracts. The contractile tissue of the myocardium is composed of fibers with the characteristic cross-striations of muscular tissue. The cardiac muscle cells are interconnected to form a network spiral or circular bundles (Figure 5–9). These interlacing circular bundles effectively connect all the parts of the heart together. Collectively, the spiral bundles form a dense network called the **fibrous skeleton of the heart**, which reinforces the internal portion of the myocardium. Specifically, modified tissue fibers of the myocardium constitute the conduction system of the heart (i.e., the sinoatrial [SA] node, the atrioventricular [AV] node, the AV bundle of His, and the Purkinje fibers) (discussed in more detail in Chapter 12).

The **endocardium** is a glistening white sheet of squamous epithelium that rests on a thin connective tissue layer. Located in the inner myocardial surface, it lines the heart's chambers. It contains small blood vessels and a few bundles of smooth muscles. It is continuous with the endothelium of the great blood vessels—the superior and inferior vena cava.

FIGURE 5-9 View of the spiral and circular arrangement of the cardiac muscle bundles.



Blood Supply of the Heart

Arterial Supply

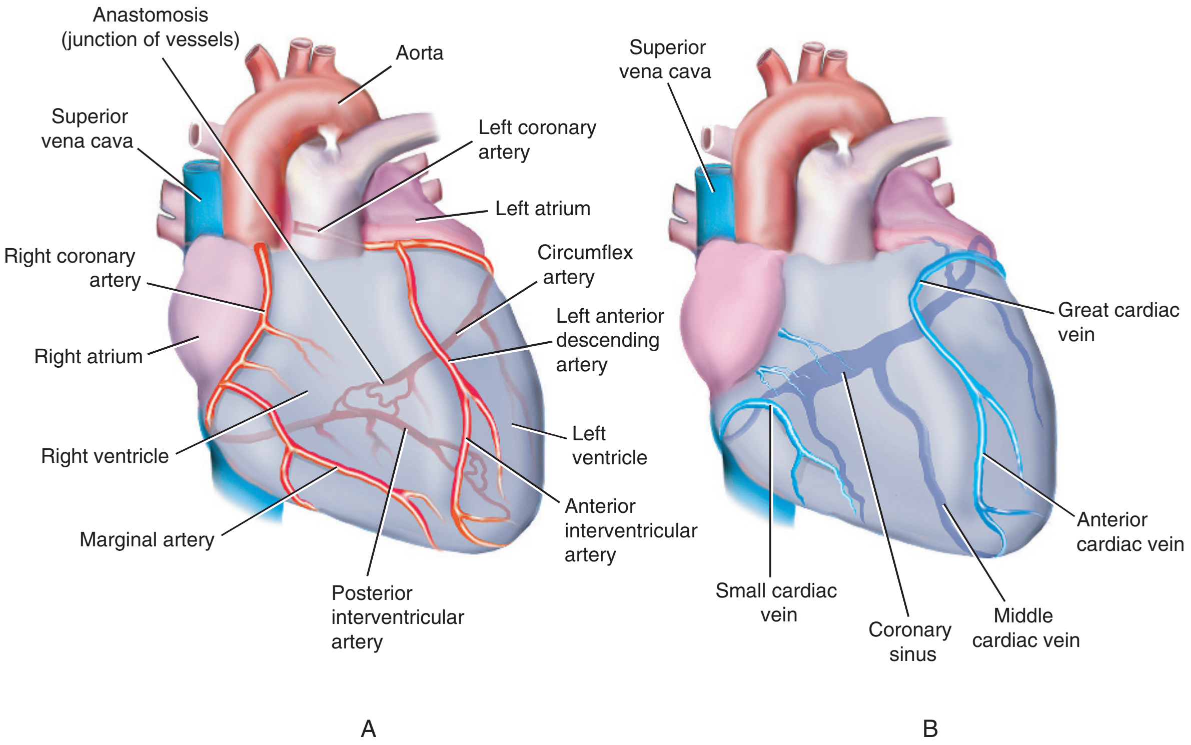
The blood supply of the heart originates directly from the aorta by means of two arteries: the **left coronary artery** and the **right coronary artery**.

The left coronary artery divides into the **circumflex branch** and the **anterior interventricular branch** (Figure 5–10A). The circumflex branch runs posteriorly and supplies the left atrium and the posterior wall of the left ventricle. The anterior interventricular branch travels toward the apex of the heart and supplies the anterior walls of both ventricles and the interventricular septum. The right coronary artery supplies the right atrium and then divides into the **marginal branch** and the **posterior interventricular branch**. The marginal branch supplies the lateral walls of the right atrium and right ventricle. The posterior interventricular branch supplies the posterior wall of both ventricles.

Venous Drainage

The venous system of the heart parallels the coronary arteries. Venous blood from the anterior side of the heart empties into the **great cardiac veins**; venous blood from the posterior portion of the heart is collected by the **middle cardiac vein** (see Figure 5–10B). The great and middle cardiac veins merge and empty into a large venous cavity within the posterior wall of the right atrium called the **coronary sinus**. A small amount of venous blood is collected by the **Thebesian veins**, which empty directly into both the right and left atrium. The venous drainage that flows into the left atrium contributes to the normal anatomic shunt, the phenomenon whereby oxygenated blood mixes with deoxygenated blood (this concept is discussed in more detail in Chapter 6).

FIGURE 5-10 Coronary circulation: **(A)** arterial vessels; **(B)** venous vessels.


Anastomosis (junction of vessels)
Aorta
Superior vena cava
Left coronary artery
Left atrium
Right coronary artery
Circumflex artery
Left anterior descending artery
Right atrium
Right ventricle
Left ventricle
Anterior interventricular artery
Marginal artery
Posterior interventricular artery
A
Superior vena cava
Great cardiac vein
Anterior cardiac vein
Small cardiac vein
Coronary sinus
Middle cardiac vein
B

Clinical Connection 5-5

Myocardial Infarction—Common Diagnostic and Treatment Interventions for Blocked Coronary Arteries

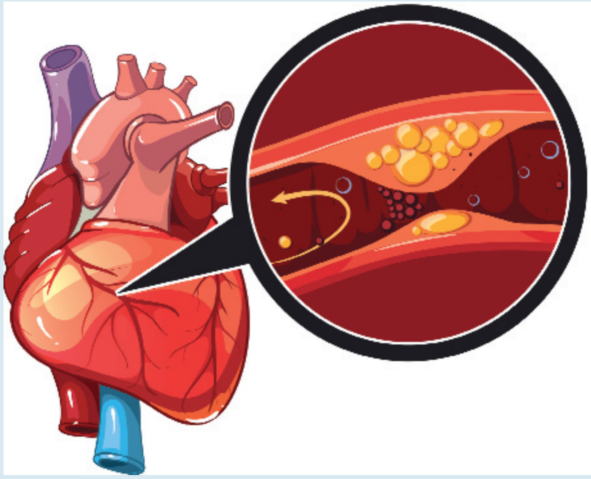
Myocardial infarction (heart attack) is caused by a prolonged lack of blood flow—and oxygen delivery—to a part of the cardiac muscle. The most common cause of a myocardial infarction is **atherosclerosis,** which is the gradual buildup of fatty, calcified plaques (collections) of cholesterol on the internal walls of the coronary arteries (Figure 5–11). In addition, arteries narrowed by atherosclerosis increase the chances of the sudden formation of a blood clot on top of the plaque that can further block coronary artery blood flow. Common diagnostic and treatment interventions for a blocked coronary artery include the following:

1. **Cardiac catheterization** entails the insertion of a small plastic tube into an artery or vein and advancing it into the chambers of the heart or into the coronary arteries. Cardiac catheterization is used to examine blood flow to the heart, measure the oxygen concentration in the blood, and determine how well the heart is pumping blood. The catheter is also used to inject a radiopaque dye into the coronary arteries—a procedure called **coronary angiography** (also called **coronary arteriography**). As the dye circulates throughout the arteries, a radiograph called an **angiogram** (also called an **arteriogram**) reveals the outline of the coronary arteries and, importantly, the presence of any abnormal arterial narrowing (called stenosis) (Figure 5–12).
2. **Angioplasty** entails inserting a long, small-diameter catheter with a small balloon tip into an artery (usually the femoral artery). It is threaded through the aorta and into each of the coronary arteries.

(Continued)

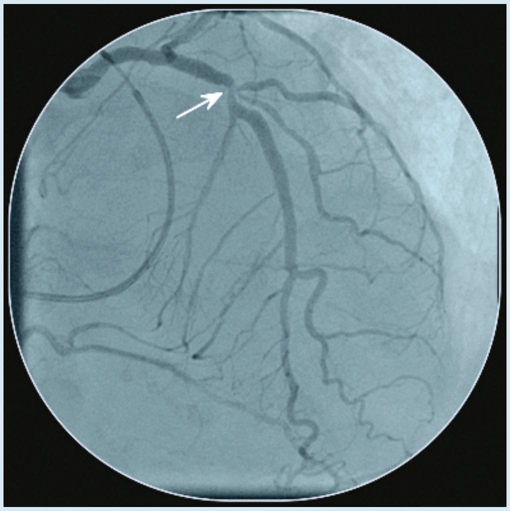
Clinical Connection 5-5, Continued

FIGURE 5-11 Myocardial infarction caused by atherosclerosis, which is the gradual buildup of fatty, calcified collections of cholesterol on the internal walls of the coronary arteries.



© iStockphoto/neyro2008

FIGURE 5-12 Left anterior descending coronary artery narrowing (stenosis) marked by the white arrow on the coronary angiography.



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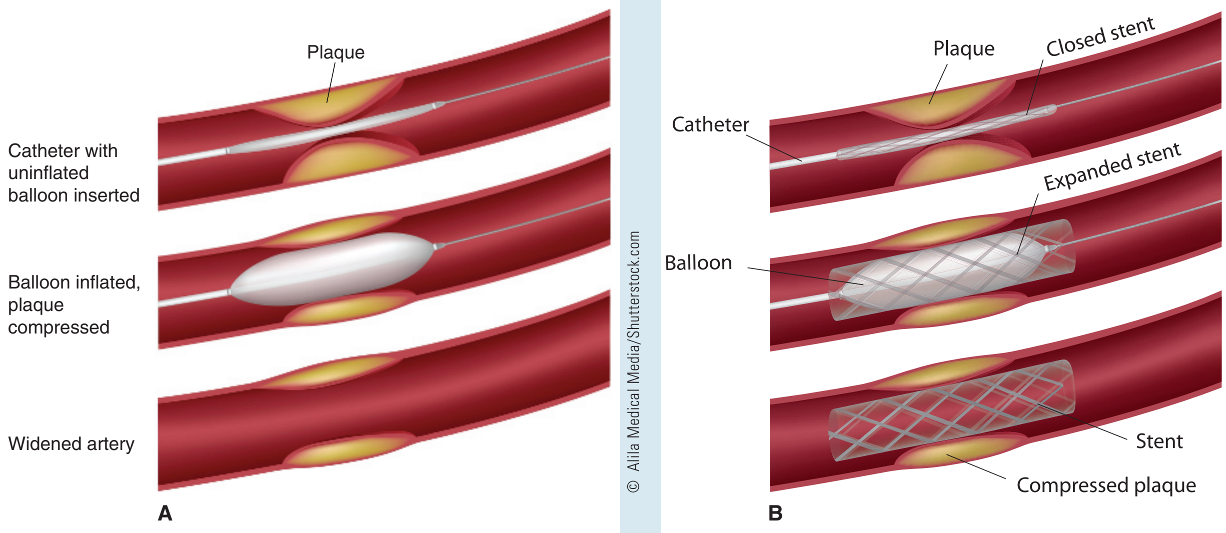
During this procedure, the catheter movement is viewed on an X-ray screen. Once the catheter is in a coronary artery, a dye is injected into it. The dye, which can be viewed on the X-ray machine, reveals any blockages that may be present. At this point, there are several types of interventional procedures the doctor may perform, including the following:

- **Balloon angioplasty**—once the balloon tip has entered the partially occluded coronary artery, it is inflated to compress and flatten the fatty deposits against the vessel walls—resulting in a wider coronary artery and an increased blood flow to the heart (Figure 5–13A).
- **Balloon angioplasty and stent**—a small metal mesh tube, called a stent, can be inserted into the artery to help prevent future blockage. The stent acts as a scaffold to provide support inside

FIGURE 5-13 **A.** Balloon angioplasty. **B.** Balloon angioplasty with stent.



Plaque
Catheter with uninflated balloon inserted
Balloon inflated, plaque compressed
Widened artery
A
Plaque
Closed stent
Catheter
Expanded stent
Balloon
Stent
Compressed plaque
B

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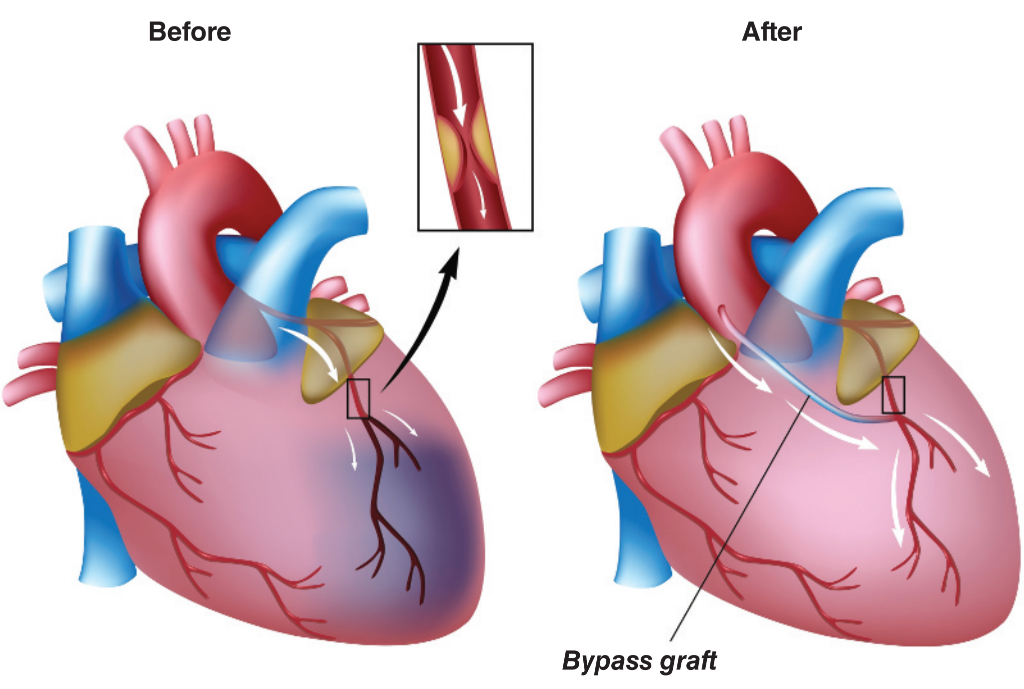
Clinical Connection 5-5, Continued

the coronary artery. Over a several-week period, the artery heals around the stent. Some stents contain medicine to reduce the risk of reblockage (Figure 5–13B).

3. A **coronary artery bypass** is a surgical procedure that entails harvesting healthy blood vessels from other parts of the patient's body (usually leg veins) and using them to bypass obstructions in the coronary arteries (Figure 5–14). The respiratory therapist routinely manages the mechanical ventilator for coronary bypass patients after surgery.

FIGURE 5-14 Coronary artery bypass graft.



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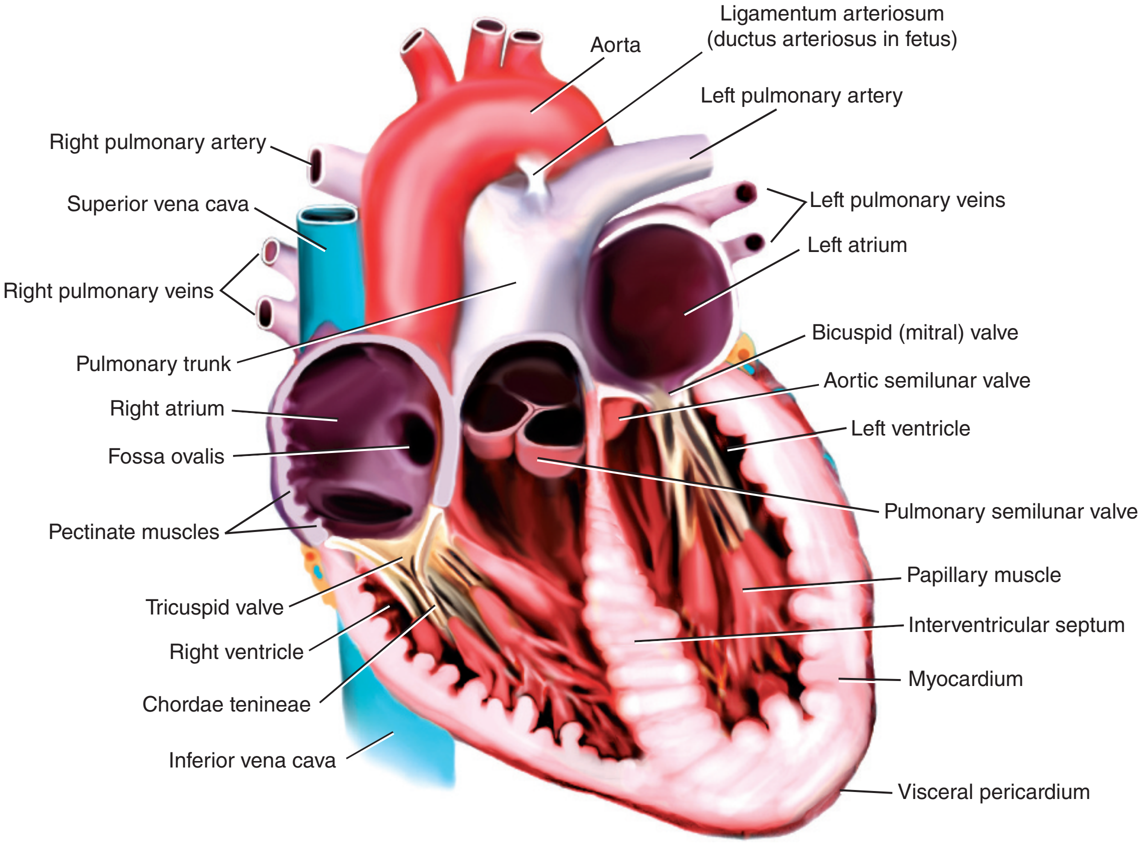
Blood Flow through the Heart

As shown in Figure 5–15, the right atrium receives venous blood from the **inferior vena cava** and **superior vena cava**. A small amount of cardiac venous blood enters the right atrium by means of the thebesian veins. This blood is low in oxygen and high in carbon dioxide. A one-way valve, the **tricuspid valve**, lies between the right atrium and the right ventricle. The tricuspid valve gets its name from its three valve leaflets, or cusps. The tricuspid leaflets are held in place by tendinous cords called **chordae tenineae**, which are secured to the ventricular wall by the **papillary muscles**. When the ventricles contract, the tricuspid valve closes, and blood leaves the right ventricle through the **pulmonary trunk** and enters the lungs by way of the right and left **pulmonary arteries**. The **pulmonary semilunar valve** separates the right ventricle from the pulmonary trunk.

After blood passes through the lungs, it returns to the left atrium by way of the **pulmonary veins**. These vessels are best seen in a posterior view of the heart (see Figure 5–4B). The returning blood is high in oxygen and low in carbon dioxide. The **bicuspid valve** (also called the **mitral valve)** lies between the left atrium and the left ventricle. This valve, which consists of two cusps, prevents blood from returning to the left atrium during ventricular contraction. Similar to the tricuspid valve, the bicuspid valve is also held in position by chordae tenineae and papillary muscles. The left ventricle pumps blood through the

FIGURE 5-15 Internal chambers and valves of the heart.


Aorta
Ligamentum arteriosum
(ductus arteriosus in fetus)
Left pulmonary artery
Right pulmonary artery
Superior vena cava
Left pulmonary veins
Left atrium
Right pulmonary veins
Pulmonary trunk
Bicuspid (mitral) valve
Aortic semilunar valve
Right atrium
Left ventricle
Fossa ovalis
Pulmonary semilunar valve
Pectinate muscles
Papillary muscle
Tricuspid valve
Interventricular septum
Right ventricle
Myocardium
Chordae tenineae
Inferior vena cava
Visceral pericardium

ascending **aorta**. The **aortic valve**, which lies at the base of the ascending aorta, has semilunar cusps (valves) that close when the ventricles relax. The closure of the semilunar valves prevent the backflow of blood into the left ventricle (see Figure 5–15).

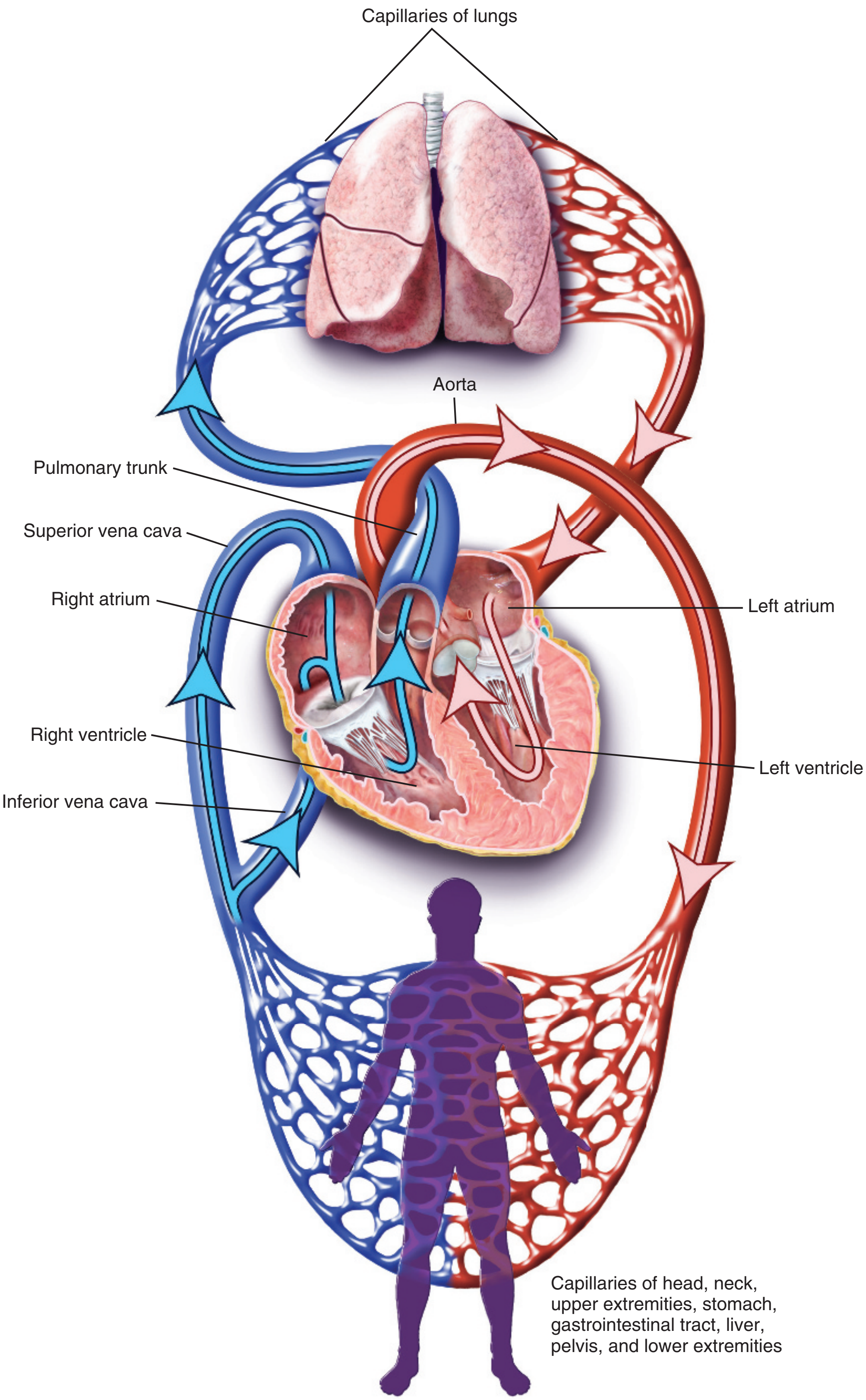
The Pulmonary and Systemic Vascular Systems

The vascular network of the circulatory system is composed of two major subdivisions: the **systemic system** and the **pulmonary system** (Figure 5–16). The pulmonary system begins with the pulmonary trunk and ends in the left atrium. The systemic system begins with the aorta and ends in the right atrium. Both systems are composed of arteries, arterioles, capillaries, venules, and veins (refer to Figure 1–43).

Arteries are vessels that carry blood away from the heart. The arteries are strong, elastic vessels that are well suited for carrying blood under high pressure in the systemic system. The arteries subdivide as they move away from the heart into smaller vessels and, eventually, into vessels called **arterioles**. Arterioles play a major role in the distribution and regulation of blood pressure and are referred to as the **resistance vessels**.

Gas exchange occurs in the **capillaries**. In the capillaries of the pulmonary system, gas exchange is called **external respiration** (gas exchange between blood and air). In the capillaries of the systemic system, gas exchange is called **internal respiration** (gas exchange between blood and tissues).

FIGURE 5-16 Pulmonary and systemic circulation. Pulmonary circulation is indicated by pink arrows; systemic circulation is indicated by blue arrows.


Capillaries of lungs
Aorta
Pulmonary trunk
Superior vena cava
Right atrium
Right ventricle
Inferior vena cava
Left atrium
Left ventricle
Capillaries of head, neck, upper extremities, stomach, gastrointestinal tract, liver, pelvis, and lower extremities

The **venules** are tiny veins continuous with the capillaries. The venules empty into the veins, which carry blood back to the heart. The veins differ from the arteries in that they are capable of holding a large amount of blood with very little pressure change. Because of this unique feature, the veins are called **capacitance vessels**. Approximately 60 percent of the body's total blood volume is contained within the venous system.

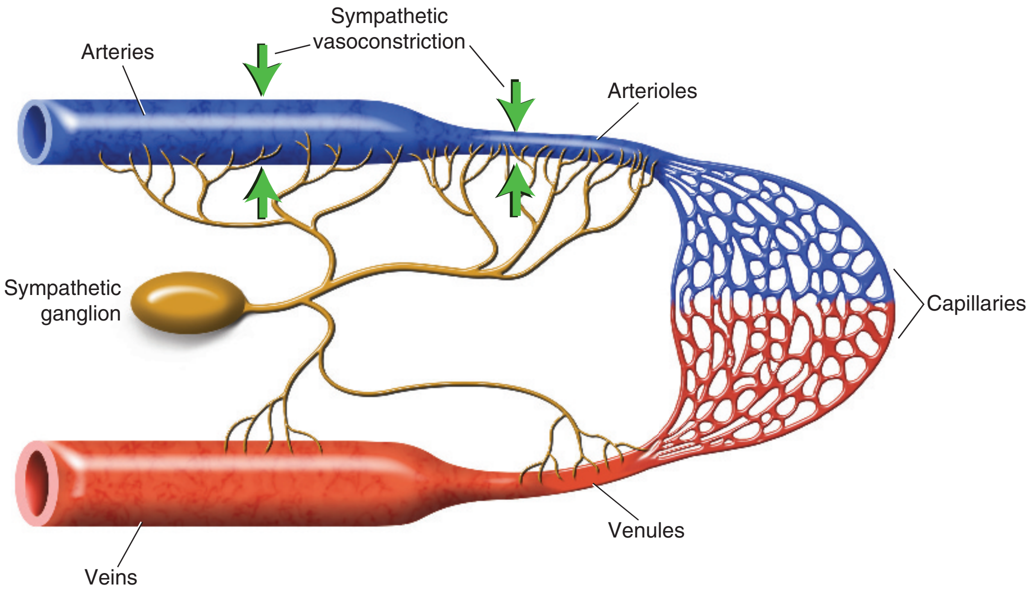
Neural Control of the Vascular System

The pulmonary arterioles and most of the arterioles in the systemic circulation are controlled by sympathetic impulses. Sympathetic fibers are found in the arteries, arterioles and, to a lesser degree, veins (Figure 5–17). The **vasomotor center**, which is located in the medulla oblongata, governs the number of sympathetic impulses sent to the vascular systems. Under normal circumstances, the vasomotor center transmits a continual stream of sympathetic impulses to the blood vessels, maintaining the vessels in a moderate state of constriction all the time. This state of vascular contraction is called the **vasomotor tone**.

The vasomotor center coordinates both vasoconstriction and vasodilation by controlling the number of sympathetic impulses that leave the medulla. For example, when the vasomotor center is activated to constrict a particular vascular region (i.e., more than the normal state of constriction), it does so by increasing the number of sympathetic impulses to that vascular area. In contrast, the vasomotor center initiates vasodilation by reducing the number of sympathetic impulses sent to a certain vascular region. (The major vascular beds in the systemic system that are *not* controlled by this mechanism are the arterioles of the heart, brain, and skeletal muscles. Sympathetic impulses to these vessels cause vasodilation.) In addition to the sympathetic control, blood flow through the large veins can be affected by abdominal and intrathoracic pressure changes.

Working together, the vasomotor center and the cardiac centers in the medulla oblongata regulate the arterial blood pressure in response to signals received from special pressure receptors located throughout the body. These pressure receptors are called **arterial baroreceptors**.

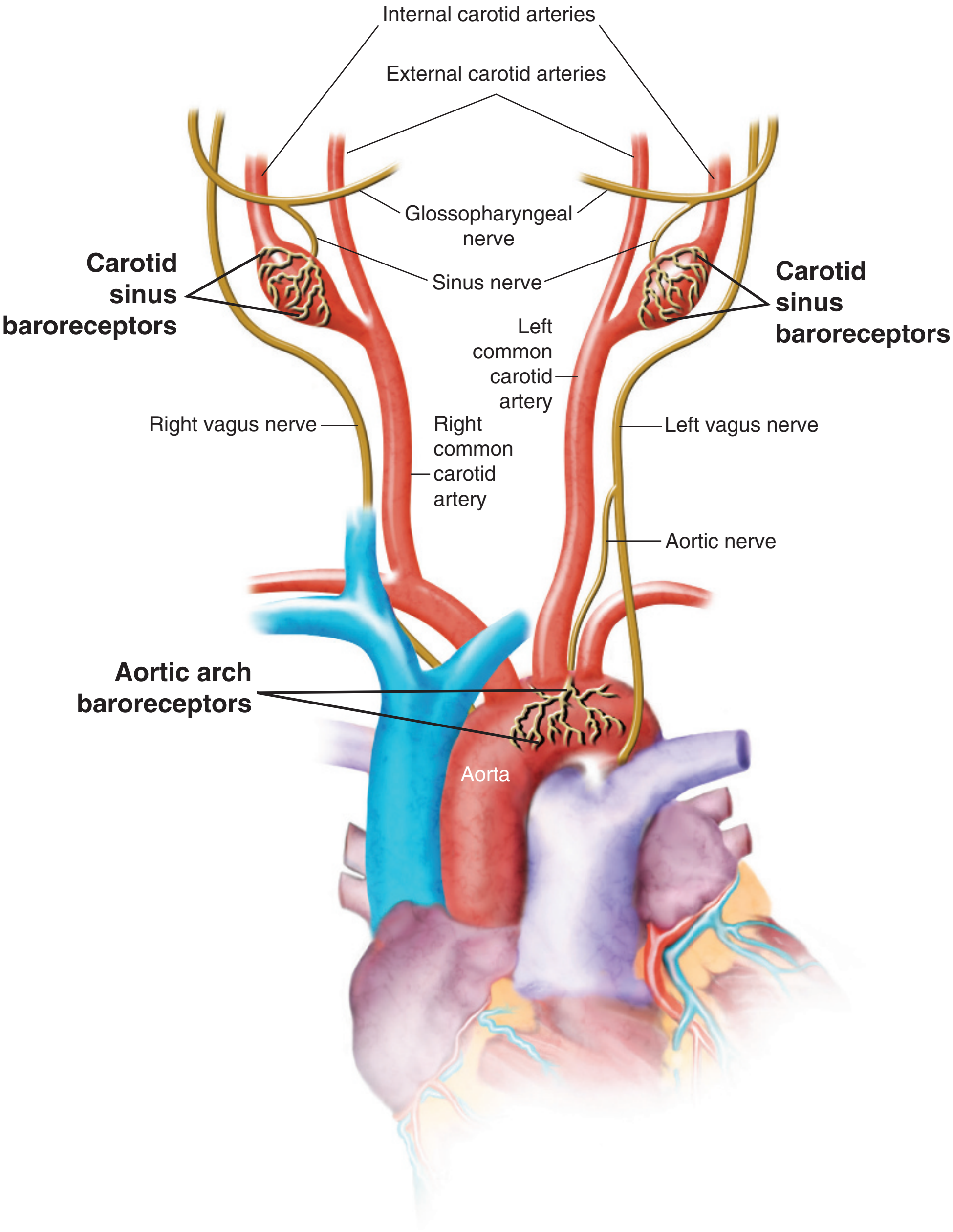
FIGURE 5-17 Neural control of the vascular system. Sympathetic neural fibers to the arterioles are especially abundant.



The Baroreceptor Reflex

Specialized stretch receptors called **baroreceptors** (also called *pressoreceptors*) are located in the walls of the carotid arteries and the aorta. In the **carotid arteries**, the baroreceptors are found in the carotid sinuses located high in the neck where the common carotid arteries divide into the external and internal carotid arteries (Figure 5–18). The walls of the carotid sinuses are thin and contain a large number of branching, vinelike nerve endings that are sensitive to stretch or distortion. The afferent fibers from the carotid sinuses travel with the **glossopharyngeal nerve** (ninth cranial) to the medulla. In the aorta, the baroreceptors are located in the **aortic arch** (see Figure 5–18). The afferent fibers from the aortic arch baroreceptors travel with the **vagus nerve** (tenth cranial).

FIGURE 5–18 Location of the arterial baroreceptors.


Internal carotid arteries
External carotid arteries
Glossopharyngeal nerve
Carotid sinus baroreceptors
Sinus nerve
Carotid sinus baroreceptors
Left common carotid artery
Right vagus nerve
Right common carotid artery
Left vagus nerve
Aortic nerve
Aortic arch baroreceptors
Aorta

The baroreceptors regulate the arterial blood pressure by initiating reflex adjustments to changes in blood pressure. For example, when the arterial pressure decreases, the neural impulses transmitted from the baroreceptors to the vasomotor and cardiac centers in the medulla also decrease. This causes the medulla to increase its sympathetic activity, which in turn causes an increase in the following:

- Heart rate
- Myocardial force of contraction
- Arterial constriction
- Venous constriction

The net result is (1) an increased cardiac output (because of an increased heart rate and stroke volume), (2) an increase in the total peripheral resistance (primarily induced by arterial constriction), and (3) the return of blood pressure toward normal. The vascular constriction occurs primarily in the abdominal region (including the liver, spleen, pancreas, stomach, intestine, kidneys, skin, and skeletal muscles).

In contrast, when the blood pressure increases, the neural impulses from the arterial baroreceptors increase. This causes the medulla to decrease its sympathetic activity, which in turn reduces both the cardiac output and the total peripheral resistance.

Finally, the baroreceptors function as short-term regulators of arterial blood pressure. That is, they respond instantly to any blood pressure change to restore the blood pressure toward normal (to the degree possible in the situation). If, however, the factors responsible for moving the arterial pressure away from normal persist for more than a few days, the arterial baroreceptors will eventually come to "accept" the new pressure as normal. For example, in individuals who have chronically high blood pressure (*hypertension*), the baroreceptors still operate, but at a higher level—in short, their operating point is reset at a higher level.

Other Baroreceptors

Baroreceptors are also found in the large arteries, large veins, and pulmonary vessels and in the cardiac walls themselves. Functionally, most of these receptors are similar to the baroreceptors in the carotid sinuses and aortic arch in that they send an increased rate of neural transmissions to the medulla in response to increased pressure. By means of these additional receptors, the medulla gains a further degree of sensitivity to venous, atrial, and ventricular pressures. For example, a slight decrease in atrial pressure initiates sympathetic activity even before there is a decrease in cardiac output and, therefore, a decrease in the arterial blood pressure great enough to be detected by the aortic and carotid baroreceptors.

Clinical Connection 5-6

Carotid Sinus Massage

In the emergency department and critical care areas, the respiratory therapist will commonly work along side the attending physician who is performing carotid sinus massage on a patient experiencing cardiac dysrhythmias. **Carotid sinus massage** involves the firm rubbing of the patient's neck over the bifurcation of the carotid artery at the angle of the jaw (see Figure 5–19). The carotid sinus contains numerous baroreceptors that monitor and maintain normal blood pressure. Massaging the carotid sinus stimulates the nerve endings located in the carotid artery walls that are capable of slowing the heart rate. Carotid sinus massage is used to slow a patient's heart rate during episodes of atrial flutter, fibrillation, and some tachycardias. It may stop the dysrhythmia completely. Carotid sinus massage may also make the discomfort of angina pectoris disappear. Do not attempt to do this on yourself or others.

Clinical Connection 5-6, Continued

FIGURE 5-19 Carotid sinus massage.

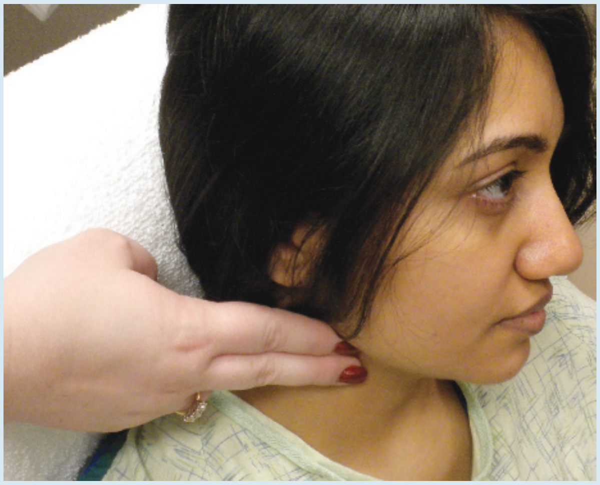


Image courtesy of Dr. George Burton

Pressures in the Pulmonary and Systemic Vascular Systems

Three different types of pressures are used to study the blood flow: intravascular, transmural, and driving.

Intravascular pressure is the actual blood pressure in the lumen of any vessel at any point, relative to the barometric pressure. This pressure is also known as the intraluminal pressure.

Transmural pressure is the difference between the intravascular pressure of a vessel and the pressure surrounding the vessel. The transmural pressure is *positive* when the pressure inside the vessel exceeds the pressure outside the vessel and *negative* when the pressure inside the vessel is less than the pressure surrounding the vessel.

Driving pressure is the difference between the pressure at one point in a vessel and the pressure at any other point downstream in the vessel.

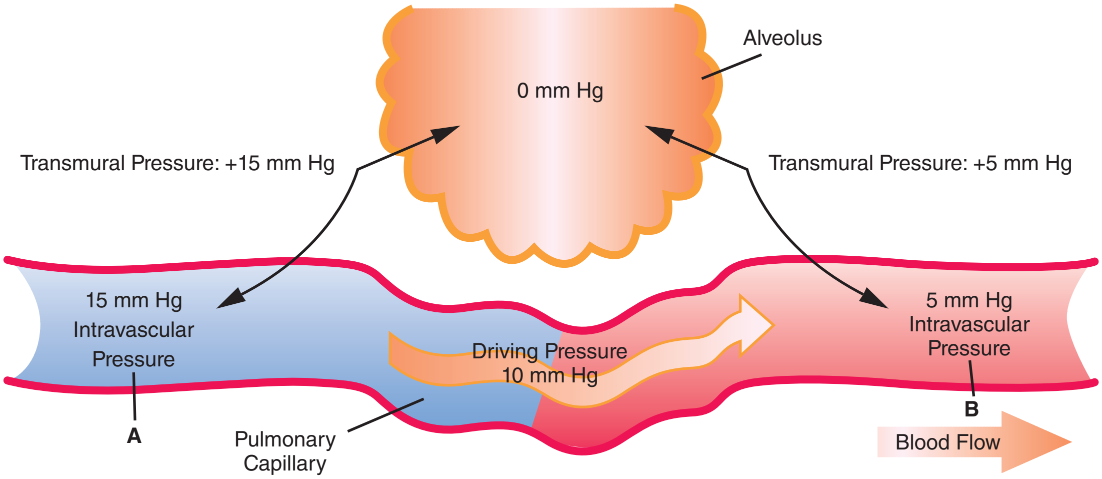
Figure 5–20 illustrates the different types of pressures used to study the flow of blood.

Clinical Connection 5-7

Case Study—Automobile Accident Victim with Massive Blood Loss

In the Clinical Application Case 1 (page 250), the respiratory therapist is called to help care for a 16-year-old girl involved in an automobile accident. In the emergency room, the patient is unconscious and hypotensive from massive blood loss. The case illustrates (1) the activation of the baroreceptor reflex, (2) hypovolemia and how it relates to preload, (3) negative transmural pressure, and (4) the effects of gravity blood flow. This case further illustrates how these mechanisms can be offset by lowering the patient's head and elevating the legs and replacing the volume of blood loss with Ringer's solution.

FIGURE 5-20 Schematic of a blood vessel and an alveolus, showing the types of blood pressures used to study blood flow. Within the blood vessel, the intravascular pressure at point A is 15 mm Hg, and the intravascular pressure at point B is 5 mm Hg. The pressure within the alveolus (which represents the pressure surrounding the blood vessel) is zero. In view of these numbers, the following can be stated: (1) The transmural pressure at point A is +15 mm Hg, (2) the transmural pressure at point B is +5 mm Hg, and (3) the driving pressure between point A and point B is 10 mm Hg.


Alveolus
0 mm Hg
Transmural Pressure: +15 mm Hg
Transmural Pressure: +5 mm Hg
15 mm Hg
Intravascular
Pressure
Driving Pressure
10 mm Hg
5 mm Hg
Intravascular
Pressure
A
Pulmonary
Capillary
B
Blood Flow

The Cardiac Cycle and Its Effect on Blood Pressure

The arterial blood pressure rises and falls in a pattern that corresponds to the phases of the cardiac cycle. When the ventricles contract (ventricular systole), blood is forced into the pulmonary artery and the aorta, and the pressure in these arteries rises sharply. The maximum pressure generated during ventricular contraction is the **systolic pressure**. When the ventricles relax (ventricular diastole), the arterial pressure drops. The lowest pressure that remains in the arteries prior to the next ventricular contraction is the **diastolic pressure** (Figure 5–21). In the systemic system, normal systolic pressure is about 120 mm Hg and normal diastolic pressure is about 80 mm Hg. In the pulmonary system, the normal systolic pressure is about 25 mm Hg and the normal diastolic pressure is about 8 mm Hg (Figure 5–22).

FIGURE 5-21 Sequence of cardiac contraction: **(A)** ventricular diastole and atrial systole; **(B)** ventricular systole and atrial diastole.

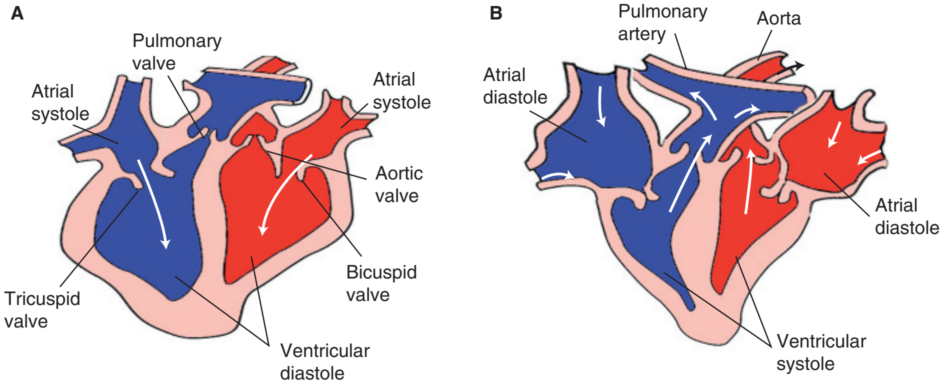
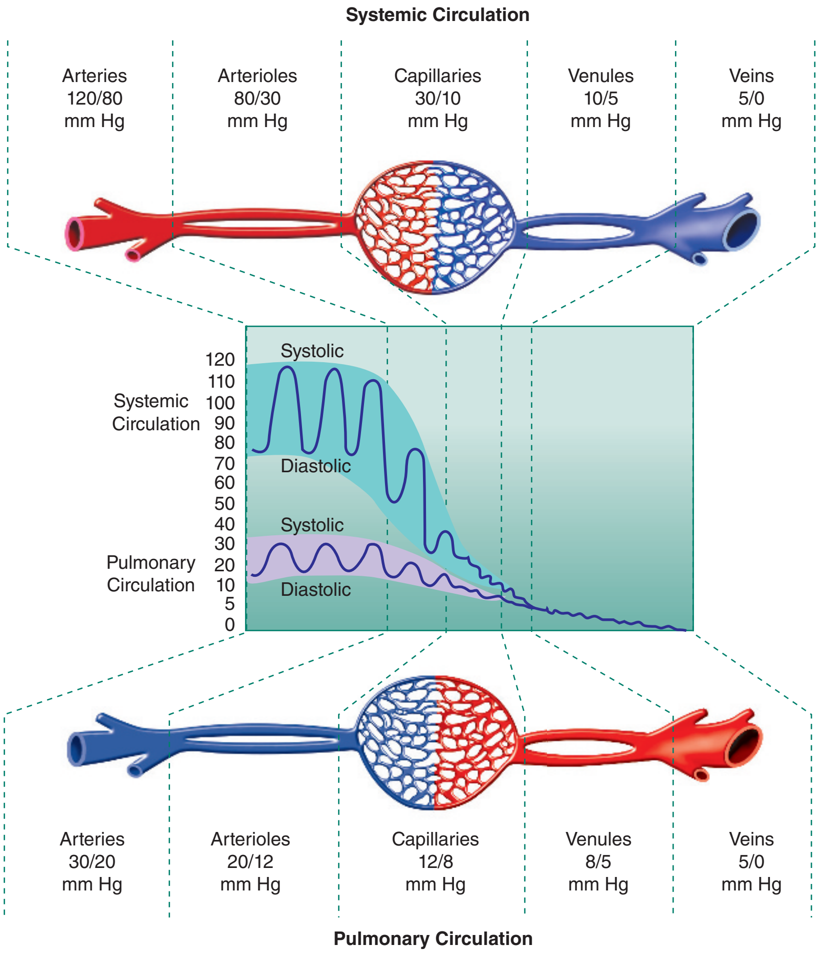

A
Pulmonary
valve
Atrial
systole
Atrial
systole
Aortic
valve
Bicuspid
valve
Tricuspid
valve
Ventricular
diastole
B
Pulmonary
artery
Aorta
Atrial
diastole
Atrial
diastole
Ventricular
systole

FIGURE 5-22 Summary of diastolic and systolic pressures in various segments of the circulatory system. Red vessels: oxygenated blood; blue vessels: deoxygenated blood.


Systemic Circulation
Arteries
120/80
mm Hg
Arterioles
80/30
mm Hg
Capillaries
30/10
mm Hg
Venules
10/5
mm Hg
Veins
5/0
mm Hg
Systemic
Circulation
120
110
100
90
80
70
60
50
40
30
20
10
5
0
Pulmonary
Circulation
Systolic
Diastolic
Systolic
Diastolic
Arteries
30/20
mm Hg
Arterioles
20/12
mm Hg
Capillaries
12/8
mm Hg
Venules
8/5
mm Hg
Veins
5/0
mm Hg
Pulmonary Circulation

The mean arterial blood pressure (MAP) can be estimated by measuring the systolic blood pressure (SBP) and the diastolic blood pressure (DBP) and using the following formula:

$$\text{MAP} = \frac{\text{SBP} + (2 \times \text{DBP})}{3}$$

For example, the mean arterial blood pressure of the systemic system, which has a systolic pressure of 120 mm Hg and a diastolic pressure of 80 mm Hg, would be calculated as follows:

$$\begin{aligned}\text{MAP} &= \frac{\text{SBP} + (2 \times \text{DBP})}{3}\\ &= \frac{120 + (2 \times 80)}{3}\\ &= \frac{280}{3}\\ &= 93 \text{ mm Hg}\end{aligned}$$

In the normal adult, the MAP ranges between 80 to 100 mm Hg. When the MAP falls below 60 mm Hg, the blood flow through the brain and kidneys is significantly reduced. Organ deterioration and failure may occur in minutes.

The pulmonary circulation is a low-pressure system. The mean pressure in the pulmonary artery is about 15 mm Hg, and the mean pressure in the left atrium is about 5 mm Hg. Thus, the driving pressure needed to move blood through the lungs is 10 mm Hg. In contrast, the mean intraluminal pressure in the aorta is about 100 mm Hg and the mean right atrial pressure about 2 mm Hg, making the driving pressure through the systemic system about 98 mm Hg. Compared with the pulmonary circulation, the pressure in the systemic system is about 10 times greater. Figure 5–23 shows the mean intraluminal blood pressures throughout both the pulmonary and systemic vascular systems.

The surge of blood rushing into the arterial system during each ventricular contraction causes the elastic walls of the arteries to expand. When the ventricular contraction stops, the pressure drops almost immediately and the arterial walls recoil. This alternating expansion and recoil of the arterial wall can be felt as a pulse in systemic arteries that run close to the skin's surface. Figure 5–24 shows the major sites where a pulse can be detected by palpation.

The Blood Volume and Its Effect on Blood Pressure

The volume of blood ejected from the ventricle during each contraction is called the **stroke volume**. Normally, the stroke volume ranges between 40 and 80 mL. The total volume of blood discharged from the

FIGURE 5-23 Mean intraluminal blood pressure (in mm Hg) at various points in the pulmonary and systemic vascular systems.

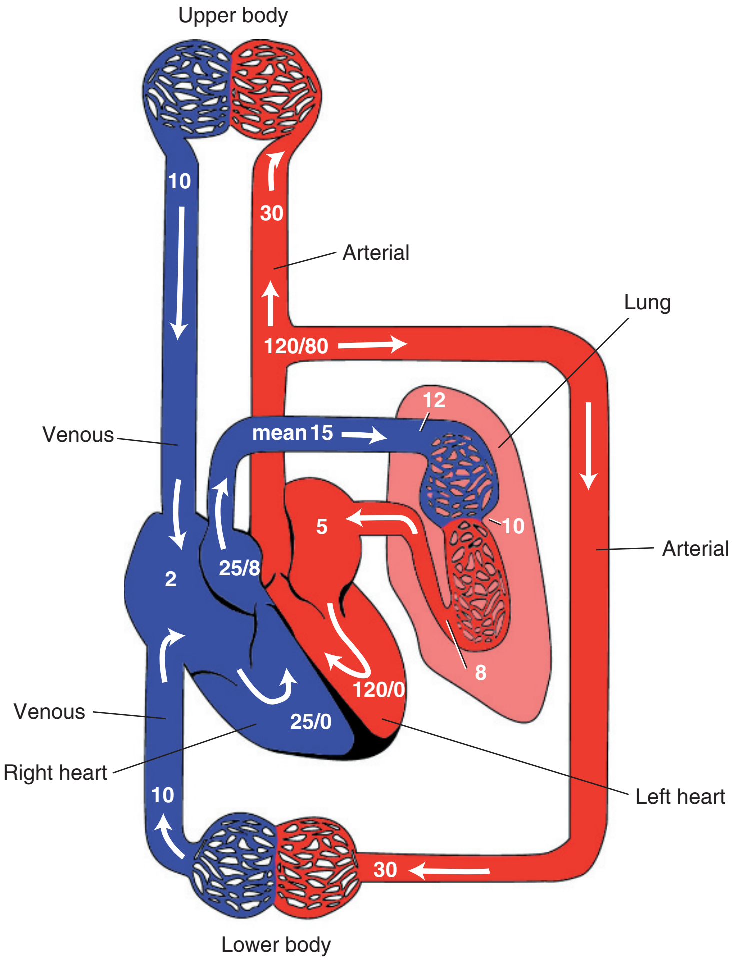
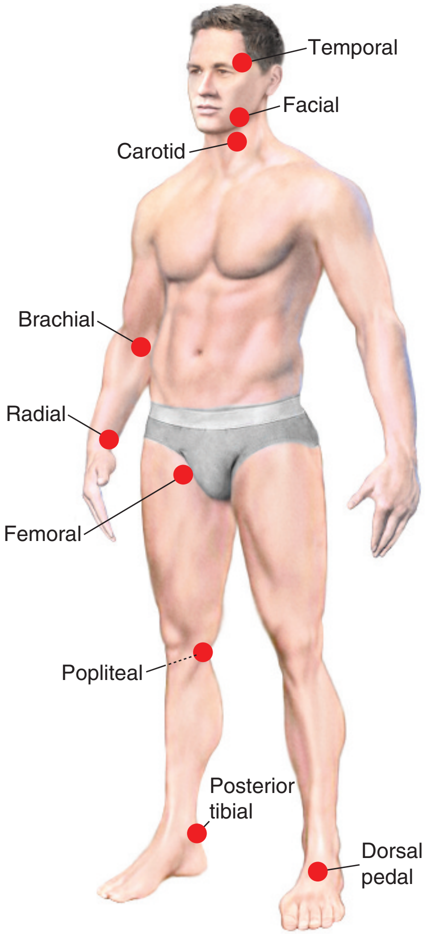


FIGURE 5-24 Major sites where an arterial pulse can be detected.



ventricles per minute is called **cardiac output**. The cardiac output (CO) is calculated by multiplying the stroke volume (SV) by the heart rate (HR) per minute (CO = SV × HR). Thus, if the stroke volume is 70 mL, and the heart rate is 72 beats per minute (bpm), the cardiac output is 5040 mL/min.

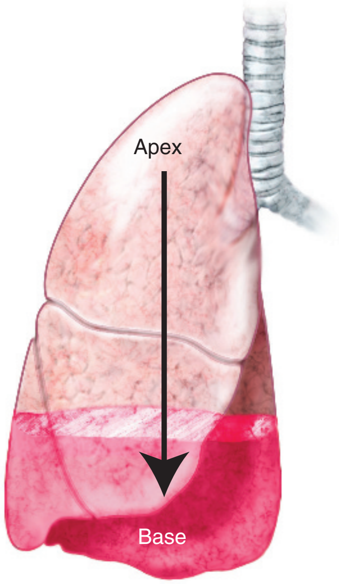
Under normal circumstances, the cardiac output directly influences blood pressure. In other words, *when either the stroke volume or heart rate increases, the blood pressure increases.* Conversely, when the stroke volume or heart rate decreases, the blood pressure decreases.

Although the total blood volume varies with age, body size, and sex, the normal adult volume is about 5 L. Of this volume, about 75 percent is in the systemic circulation, 15 percent in the heart, and 10 percent in the pulmonary circulation. Overall, about 60 percent of the total blood volume is in the veins, and about 10 percent is in the arteries. Normally, the pulmonary capillary bed contains about 75 mL of blood, although it has the capacity of about 200 mL.

The Distribution of Pulmonary Blood Flow

In the upright lung, blood flow progressively decreases from the base to the apex (Figure 5–25). This linear distribution of blood is a function of (1) **gravity**, (2) **cardiac output**, and (3) **pulmonary vascular resistance**.

FIGURE 5–25 Distribution of pulmonary blood flow. In the upright lung, blood flow steadily increases from the apex to the base.



Gravity

Because blood is a relatively heavy substance, it is **gravity dependent**; that is, it naturally moves to the portion of the body, or portion of the organ, that is closest to the ground. In the average lung, there is a distance of about 30 cm between the base and the apex. The blood that fills the lung from the bottom to the top is analogous to a column of water 30 cm long and, therefore, exerts a pressure of about 30 cm H_2O (22 mm Hg) between the base and apex. Because the pulmonary artery enters each lung about midway between the top and bottom of the lung, the pulmonary artery pressure must be greater than 15 cm H_2O (11 mm Hg) to overcome the gravitational force and, thereby, supply blood to the lung apex. For this reason, most of the blood flows through (or falls into) the lower half of the lung—the gravity-dependent portion of the lung.

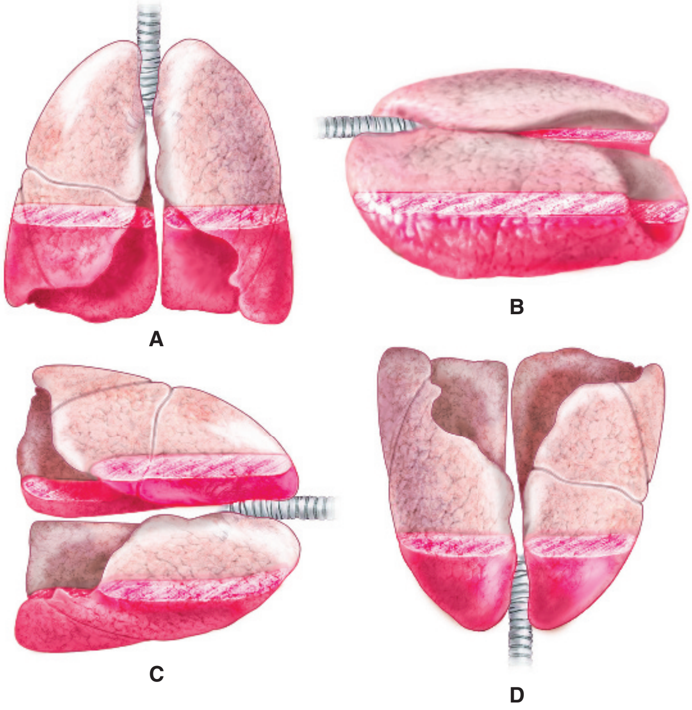
As a result of the gravitational effect on blood flow, the intraluminal pressures of the vessels in the gravity-dependent area (lower lung region) are greater than the intraluminal pressures in the least gravity-dependent area (upper lung region). The high intraluminal pressure of the vessels in the gravity-dependent area causes the vessels to distend. As the vessels widen, the vascular resistance decreases and, thus, permits blood flow to increase. The fact that blood flow is enhanced as the vascular system widens is according to Poiseuille's law for flow ($\dot{V} = Pr^4$).

The position of the body can significantly change the gravity-dependent portion of the lungs. For example, when an individual is in the supine position (lying on the back), the gravity-dependent area is the posterior portion of the lungs; when an individual is in the prone position (lying on the stomach), the gravity-dependent region is the anterior portion of the lungs; when the person is lying on the side, the lower, lateral half of the lung nearest the ground is gravity dependent; when an individual is suspended upside down, the apices of the lungs become gravity dependent (Figure 5–26).

Figure 5–27 uses a three-zone model to illustrate the effects of gravity and alveolar pressure on the distribution of pulmonary blood flow.

In **Zone 1** (the least gravity-dependent area), the alveolar pressure is sometimes greater than both the arterial and the venous intraluminal pressures. As a result, the pulmonary capillaries can be compressed, and blood is prevented from flowing through this region. Under normal circumstances, this situation does not occur because the pulmonary arterial pressure (generated by the cardiac output) is

FIGURE 5-26 Blood flow normally moves into the gravity-dependent areas of the lungs. Thus, body position affects the distribution of the pulmonary blood flow as illustrated in the **(A)** erect, **(B)** supine, **(C)** lateral, and **(D)** upside-down positions.



usually sufficient to raise the blood to the top of the lungs and to overcome the alveolar pressure. There are, however, a variety of conditions—such as severe hemorrhage, dehydration, and positive pressure ventilation—that can result in the alveolar pressure being higher than the arterial and venous pressures. When the alveoli are ventilated but not perfused, no gas exchange can occur, and **alveolar dead space** is said to exist (refer to Figure 2–51).

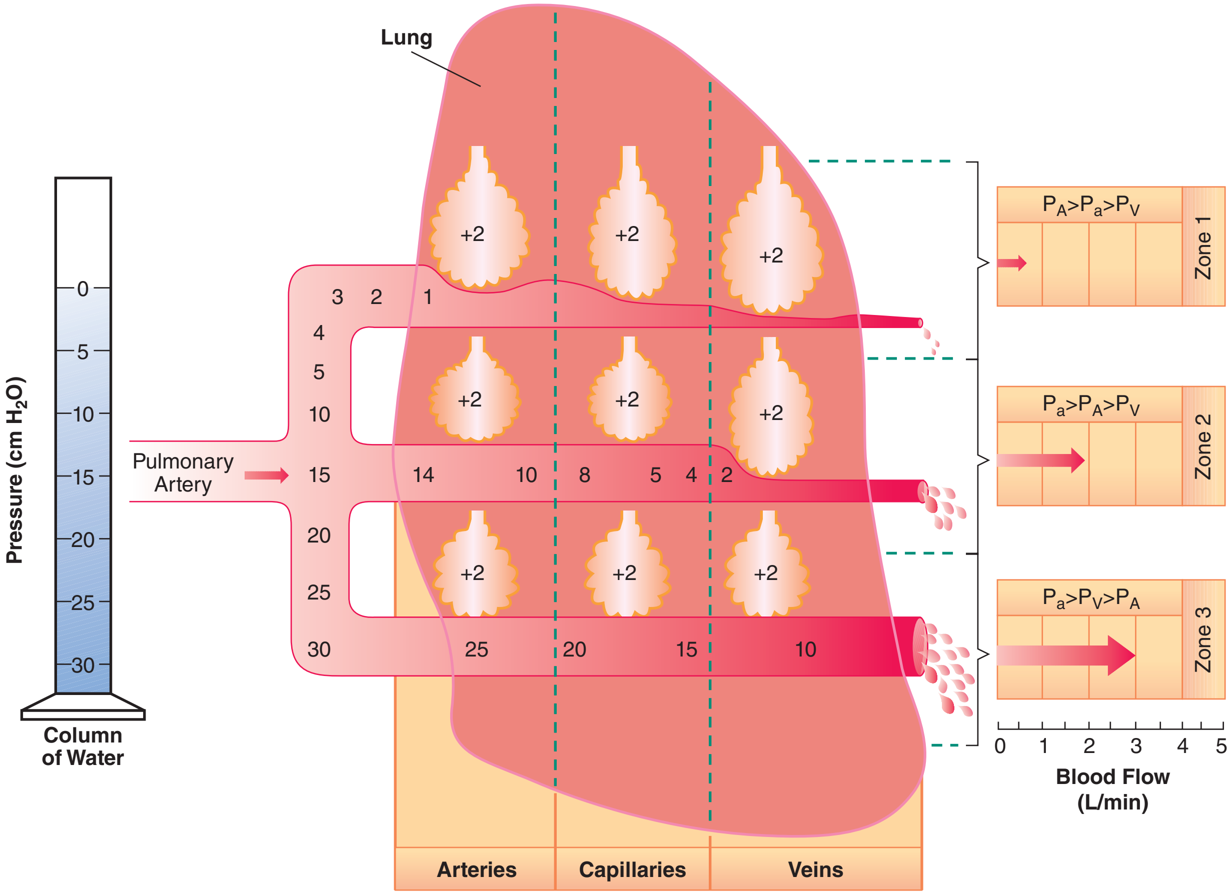
In **Zone 2**, the arterial pressure is greater than the alveolar pressure, and therefore, the pulmonary capillaries are perfused. Because the alveolar pressure is greater than the venous pressure, the effective driving pressure for blood flow is determined by the pulmonary arterial pressure minus the alveolar pressure—not the normal arterial-venous pressure difference. Thus, because the alveolar pressure is essentially the same throughout all the lung regions, and because the arterial pressure progressively increases toward the gravity-dependent areas of the lung, the effective driving pressure (arterial pressure minus alveolar pressure) steadily increases down the vertical axis of Zone 2. As a result, from the beginning of the upper portion of Zone 2 (the point at which the arterial pressure equals the alveolar pressure) to the lower portion of Zone 2 (the point at which the venous pressure equals the alveolar pressure) the flow of blood progressively increases.

In **Zone 3** (gravity-dependent area), both the arterial and the venous pressures are greater than the alveolar pressure and, therefore, blood flow through this region is constant. Because the arterial pressure and venous pressure both increase equally downward in Zone 3, the arterial-venous pressure difference and, therefore, blood flow is essentially the same throughout all of Zone 3.

Cardiac Output

As described earlier, the cardiac output is equal to the stroke volume times the heart rate ($CO = SV \times HR$). The stroke volume is determined by (1) ventricular preload, (2) ventricular afterload, and (3) myocardial contractility.

FIGURE 5-27 Relationship among gravity, alveolar pressure (P_A), pulmonary arterial pressure (P_a), and pulmonary venous pressure (P_v) in different lung zones. Note: The +2 cm H_2O pressure in the alveoli (e.g., during expiration) was arbitrarily selected for this illustration.


Lung
Pressure (cm H2O)
0
5
10
15
20
25
30
Column of Water
Pulmonary Artery
+2
3 2 1
4
5
10
15 14 10 8 5 4 2
20
25
30 25 20 15 10
PA>Pa>PV
Zone 1
Pa>PA>PV
Zone 2
Pa>PV>PA
Zone 3
0 1 2 3 4 5
Blood Flow (L/min)
Arteries
Capillaries
Veins

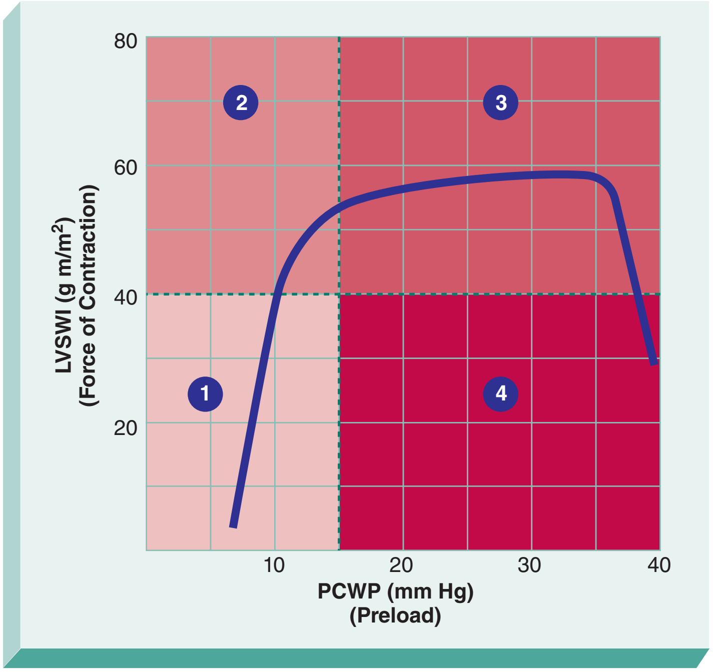
Ventricular Preload

Ventricular preload refers to the degree that the myocardial fiber is stretched prior to contraction (*end-diastole*). Within limits, the more the myocardial fiber is stretched during diastole (*preload*), the more strongly it will contract during systole and, therefore, the greater the myocardial contractility will be. This mechanism enables the heart to convert an increased venous return into an increased stroke volume. Beyond a certain point, however, the cardiac output does not increase as the preload increases.

Because the degree of myocardial fiber stretch (preload) is a function of the pressure generated by the volume of blood returning to the ventricle during diastole, ventricular preload is reflected in the **ventricular end-diastolic pressure (VEDP)**—which, in essence, reflects the **ventricular end-diastolic volume (VEDV)**. In other words, as the VEDV increases or decreases, the VEDP (and, therefore, the cardiac output) increases or decreases, respectively. It should be noted, however, that similar to lung compliance (C_L), VEDP and VEDV are also influenced by ventricular compliance. For example, when the ventricular compliance is decreased as a result of disease, the VEDP increases significantly more than the VEDV.

The relationship between the VEDP (degree of myocardial stretch) and cardiac output (stroke volume) is known as the **Frank-Starling curve** (Figure 5–28).

FIGURE 5-28 Frank-Starling curve. The Frank-Starling curve shows that the more the myocardial fiber is stretched as a result of the blood pressure that develops as blood returns to the chambers of the heart during diastole, the more the heart muscle will contract during systole. In addition, the heart muscle will contract with greater force. The stretch produced within the myocardium at end-diastole is called preload. Clinically, it would be best to determine the preload of the left ventricle by measuring the end-diastolic pressure of the left ventricle or left atrium. However, because this practice would be impractical at the patient's bedside, the best preload approximation of the left heart is the pulmonary capillary wedge pressure (PCWP). As shown here, the relationship of the PCWP (preload) to the left ventricular stroke work index (LVSWI) (force of contraction) may appear in four quadrants: (1) hypovolemia, (2) optimal function, (3) hypervolemia, and (4) cardiac failure.



Ventricular Afterload

Ventricular afterload is defined as the force against which the ventricles must work to pump blood. It is determined by several factors, including (1) the volume and viscosity of the blood ejected, (2) the peripheral vascular resistance, and (3) the total cross-sectional area of the vascular space into which blood is ejected. The arterial systolic blood pressure best reflects the ventricular afterload. For example, as the arterial systolic pressure increases, the resistance (against which the heart must work to eject blood) also increases. Clinically, this condition is particularly serious in the patient with congestive heart failure and low stroke volume. By reducing the peripheral resistance (*afterload reduction*) in such patients, the stroke volume increases with little or no change in the blood pressure. This is because blood pressure (BP) is a function of the cardiac output (CO) times the systemic vascular resistance (SVR): BP = CO × SVR.

Myocardial Contractility

Myocardial contractility may be regarded as the force generated by the myocardium when the ventricular muscle fibers shorten. In general, when the contractility of the heart increases or decreases, the cardiac output increases or decreases, respectively.

There is no single measurement that defines contractility in the clinical setting. Changes in contractility, however, can be inferred through clinical assessment (e.g., pulse, blood pressure, skin temperature) and serial

Clinical Connection 5-8

Congestive Heart Failure

Congestive heart failure (CHF) (also called left-heart failure) is the inability of the *left* ventricle to pump blood effectively. When a patient has CHF, the right ventricle continues to pump blood to the lungs, but the left ventricle does not adequately pump the returning blood from the lungs into the systemic circulation. As a result, the vascular system in the lungs become engorged with blood, the pulmonary capillary blood pressure increases, and fluid leaks out of the capillaries into the alveoli—causing the condition known as **pulmonary edema.** The respiratory therapist will frequently treat patients suffering from pulmonary edema. These patients are difficult to oxygenate—even on 100 percent oxygen. Additional therapy includes diuretics to reduce excess fluids, and **bi-level positive airway pressure (BiPAP)** ventilation until sufficient fluid has been eliminated by the kidneys.

hemodynamic measurements (discussed in Chapter 15). An increase in myocardial contractility is referred to as **positive inotropism**. A decrease in myocardial contractility is referred to as **negative inotropism**.

Pulmonary Vascular Resistance

Circulatory resistance is approximated by dividing the mean arterial pressure (MAP) by the cardiac output (CO):

$$\text{Resistance} = \frac{\text{MAP}}{\text{CO}}$$

In general, when the vascular resistance increases, the blood pressure increases (which, in turn, increases the ventricular afterload). Because of this relationship, blood pressure monitoring can be used to reflect pulmonary or systemic resistance. That is, when resistance increases or decreases, the blood pressure will increase or decrease.

In the pulmonary system, there are several known mechanisms that change the vascular resistance. Such mechanisms are classified as either *active* or *passive mechanisms.*

Active Mechanisms Affecting Vascular Resistance

Active mechanisms that affect vascular resistance include abnormal blood gases, pharmacologic stimulation, and pathologic conditions that have a direct effect on the vascular system.

Clinical Connection 5-9

Case Study—Left Ventricular Heart Failure and Pulmonary Edema

In the Clinical Application Case 2 (page 251), the respiratory therapist is called to help care for a 72-year-old woman with left ventricular heart failure and pulmonary edema (congestive heart failure). The case illustrates the effects of high blood pressure on (1) ventricular afterload, (2) ventricular contractility, (3) ventricular preload, and (4) transmural pressure. This case further illustrates how positive inotropic vasodilators and diuretic agents work to offset the adverse effects of left ventricular heart failure.

Abnormal Blood Gases

- Decreased P_{O_2} (hypoxia)
- Increased P_{CO_2} (hypercapnia)
- Decreased pH (acidemia)

The pulmonary vascular system constricts in response to a decreased alveolar oxygen pressure (**hypoxia**). The exact mechanism of this phenomenon is unknown. Some investigators suggest that alveolar hypoxia causes the lung parenchyma to release a substance that produces vasoconstriction. It is known, however, that the partial pressure of oxygen in the *alveoli* (PA_{O_2})—not the partial pressure of oxygen of the *capillary blood* P_{CO_2}—controls this response. The effect of hypoxic vasoconstriction is to direct blood away from the hypoxic lung regions to lung areas that have a higher partial pressure of oxygen.

Clinically, when the number of hypoxic regions becomes significant (e.g., in the advanced stages of emphysema or chronic bronchitis), generalized pulmonary vasoconstriction can develop. This can cause a substantial increase in the pulmonary vascular resistance and in the work of the right heart. This in turn leads to right ventricular hypertrophy, or *cor pulmonale.*

Pulmonary vascular resistance increases in response to an acute increase in the P_{CO_2} level (**hypercapnia**). It is believed, however, that the vasoconstriction that occurs is most likely due to the increased hydrogen ion (H^+) concentration (*respiratory acidosis*) that develops from a sudden increase in the P_{CO_2} level, rather than to the P_{CO_2} itself. This is supported by the fact that pulmonary vasoconstriction does not occur when hypercapnia is accompanied by a normal pH (*compensated respiratory acidosis*).

Pulmonary vasoconstriction develops in response to decreased pH (increased H^+ concentration), or **acidemia**, of either metabolic or respiratory origin.

Pharmacologic Stimulation. The pulmonary vessels constrict in response to various pharmacologic agents, including:

- Epinephrine
- Norepinephrine
- Dobutamine
- Dopamine
- Phenylephrine

Clinical Connection 5-10

Cor Pulmonale

Cor pulmonale is the enlargement of the *right* ventricle caused by primary lung disease. Cor pulmonale eventually results in the inability of the right ventricle to pump blood effectively to the lungs (also called right-heart failure). When the right ventricle starts to fail, blood returning to the heart backs up and pools throughout the peripheral vascular system—for example, in the liver, legs, neck veins, ankles, feet, and hands. Pulmonary emboli (clots in the pulmonary artery) and end-stage COPD are common causes of cor pulmonale. Treatment includes oxygen therapy for hypoxemia and blood anticoagulants to prevent blood clots.

Constricted pulmonary vessels relax in response to the following agents:

- Oxygen
- Isoproterenol
- Aminophylline
- Calcium-channel blocking agents

Pathologic Conditions. Pulmonary vascular resistance increases in response to a number of pathologic conditions. Some of the more common ones are as follows:

- Vessel blockage or obstruction (e.g., caused by a thrombus or an embolus, such as a blood clot, fat cell, air bubble, or tumor mass)
- Vessel wall diseases (e.g., sclerosis, polyarteritis, or scleroderma)
- Vessel destruction or obliteration (e.g., emphysema or pulmonary interstitial fibrosis)
- Vessel compression (e.g., pneumothorax, hemothorax, or tumor mass)

Pathologic disturbances in the pulmonary vascular system can develop in the arteries, arterioles, capillaries, venules, or veins. When increased vascular resistance originates in the venules or veins, the transmural pressure increases and, in severe cases, causes the capillary fluid to spill into the alveoli. This is called **pulmonary edema**. Left ventricular failure will cause the same pathologic disturbances. When the resistance originates in the arteries or arterioles, the pulmonary artery pressure will increase but the pulmonary capillary pressure will be normal or low. Regardless of the origin of the pathologic disturbance, a severe and persistent pulmonary vascular resistance is ultimately followed by an elevated right ventricular pressure, right ventricular strain, right ventricular hypertrophy, and right heart failure.

Passive Mechanisms Affecting Vascular Resistance

The term *passive mechanism* refers to a secondary change in pulmonary vascular resistance that occurs in response to another mechanical change. In other words, when a mechanical factor in the respiratory system changes, a passive increase or decrease in the caliber of the pulmonary blood vessels also occurs. Some of the more common passive mechanisms are discussed next.

Pulmonary Arterial Pressure Changes. As pulmonary arterial pressure increases, the pulmonary vascular resistance decreases (Figure 5–29). The pulmonary vascular resistance decreases because of the increase in intraluminal distending pressure, which increases the total cross-sectional areas of the pulmonary vascular system through the mechanisms of **recruitment** and **distention**.

As shown in Figure 5–30, *recruitment* means the opening of vessels that were closed or not being utilized for blood flow before the vascular pressure increased. *Distention,* on the other hand, means the stretching or widening of vessels that were open, but not to their full capacity. Both of these mechanisms increase the total cross-sectional area of the vascular system, which in turn reduces the vascular resistance. These mechanisms, however, have their limits.

Left Atrial Pressure Changes. As the left atrial pressure increases, while the lung volume and pulmonary arterial pressure are held constant, pulmonary vascular resistance decreases.

Lung Volume Changes. The effect of changes in lung volume on pulmonary vascular resistance varies according to the location of the vessel. Two major groups of vessels must be considered: (1) **alveolar vessels**—those vessels that surround the alveoli (*pulmonary capillaries*)—and (2) **extra-alveolar vessels**—the larger arteries and veins.

FIGURE 5-29 Increased mean pulmonary arterial pressure decreases pulmonary vascular resistance.

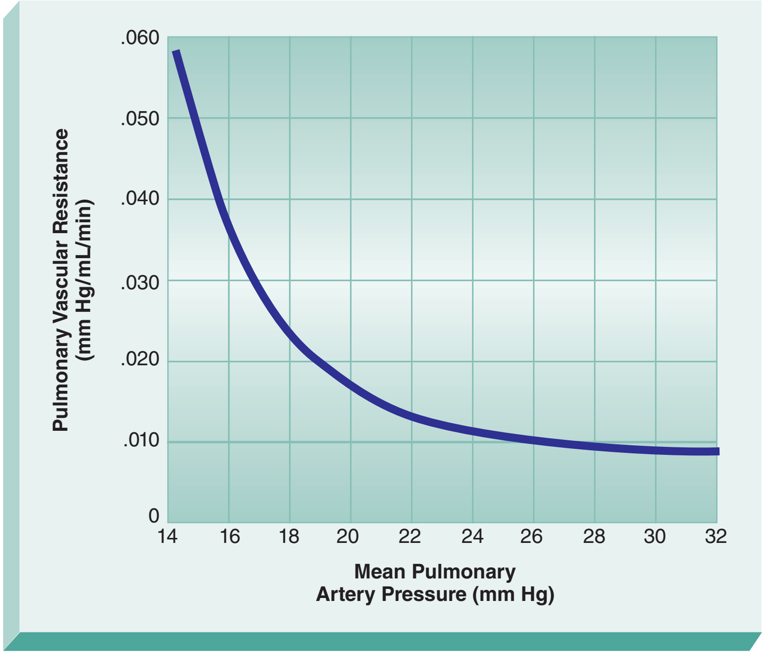


FIGURE 5-30 Schematic of the mechanisms that may be activated to decrease pulmonary vascular resistance when the mean pulmonary artery pressure increases. **A.** A group of pulmonary capillaries, one-half of which are not perfused. **B.** The previously unperfused capillaries shown in A are recruited (i.e., opened) in response to the increased pulmonary artery pressure. **C.** The increased blood pressure has distended the capillaries that are already open.

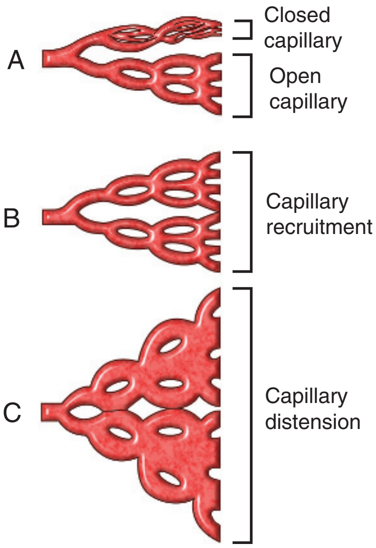
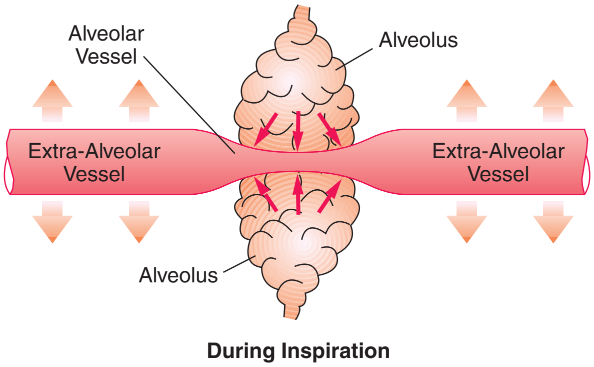

A
Closed capillary
Open capillary
B
Capillary recruitment
C
Capillary distension

FIGURE 5-31 Schematic of pulmonary vessels during inspiration. The alveolar vessels (pulmonary capillaries) are exposed to the intrapleural pressure change and are stretched and flattened. The extra-alveolar vessels expand as the intrapleural pressure becomes increasingly negative during inspiration.



Alveolar Vessels. Because the pulmonary capillary vessels are so thin, intrapleural pressure changes directly affect the anatomy of the capillaries. During normal inspiration, the alveolar vessels progressively stretch and flatten. During expiration, the alveolar vessels shorten and widen. Thus, as the lungs are inflated, the resistance offered by the alveolar vessels progressively increases (Figure 5–31). During the inspiratory phase of mechanical ventilation (*positive pressure phase*), moreover, the resistance generated by the alveolar vessels may become excessively high and, as a result, restrict the flow of pulmonary blood. The pressure difference between the alveoli and the lumen of the pulmonary capillaries is called the *transmural pressure* (see Figure 5–20).

Extra-Alveolar Vessels. The extra-alveolar vessels (the large arterioles and veins) are also exposed to the intrapleural pressure. They behave differently, however, from the pulmonary capillaries (alveolar vessels) when subjected to volume and pressure changes. That is, as the lung volume increases in response to a more negative intrapleural pressure during inspiration, the transmural pressure increases (i.e., the pressure within the vessels becomes more positive) and the extra-alveolar vessels distend

Clinical Connection 5-11

Cardiopulmonary Hazards of Positive-Pressure Ventilation

There are a number of hazards associated with positive-pressure ventilation (PPV). For example, PPV often decreases the patient's cardiac output and arterial blood pressure. This can occur because of the increased alveolar pressures that are transmitted to the intrapleural space and to the great vessels (the inferior and superior vena cava) of the thorax. The increased intrathoracic pressure compresses the great vessels and reduces the venous return to the right atrium and right ventricle. The reduced right ventricular stroke volume leads to a decreased left ventricular stroke volume—which, in turn, decreases cardiac output and arterial blood pressure.

In addition, PPV causes the mean airway pressure (P_{aw}), alveolar pressure, and intrapleural

Clinical Connection 5-11, Continued

pressure to increase. The increased alveolar pressure stretches and narrows the pulmonary capillaries that surround the alveoli. This action increases the pulmonary vascular resistance. This increases the right ventricular afterload. In normal individuals, the right ventricular stroke volume is usually maintained by the heart's ability to overcome reasonable increases in pulmonary vascular resistance. However, in the patient with a preexisting cardiovascular disease, the right ventricle may not be able to overcome these increases in pulmonary resistance. Furthermore, an increased pulmonary vascular resistance can cause overdistention of the right ventricle (cor pulmonale)—which further reduces the right ventricle's output. This action further decreases the left ventricular output and arterial blood pressure.

Finally, if **positive end-expiratory pressure (PEEP)** is added to the PPV, the patient's P_{aw} is increased even more. It is reasonable to assume that the adverse effects of positive pressure on the patient's venous return and cardiac output will be greater with PPV with PEEP than with PPV alone. Oftentimes, the respiratory therapist will perform what is called **optimal** or **best PEEP** studies to determine the point of maximum oxygenation with minimal reduction in blood pressures. Optimal PEEP can be defined as the PEEP that maximizes oxygen delivery ($D_{O_2} = Q_T \times [Ca_{O_2} \times 10]$—refer to Chapter 6). In general, the PEEP level is progressively increased in increments of 2 cm H_2O until there is a decline in the oxygen delivery. The PEEP is then turned down to the previous level—or the "best" PEEP in terms of oxygen delivery. Although the optimal PEEP level must be specifically determined for each patient, the level of PEEP typically falls in the 8 to 15 cm H_2O range.

In view of the possible hazards of PPV, the respiratory therapist must monitor all patients for signs of cardiovascular instability and closely monitor patients with preexisting cardiovascular disease for signs of decreased cardiac output and blood pressure.

(see Figure 5–31). A second factor that dilates the extra-alveolar vessels at higher lung volumes is the radial traction generated by the connective tissue and by the alveolar septa that hold the larger vessels in place throughout the lung.

Another type of extra-alveolar vessel is the so-called corner vessel, located at the junction of the alveolar septa. As the lung volume increases, the corner vessels are also pulled open (dilated) by the radial traction force created by the expansion of the alveoli (Figure 5–32).

To summarize, at low lung volumes (low distending pressures), the extra-alveolar vessels narrow and cause the vascular resistance to increase. The alveolar vessels, however, widen and cause the vascular resistance to decrease. In contrast, at high lung volumes (high distending pressures), the extra-alveolar vessels dilate and cause the vascular resistance to decrease. The alveolar vessels, however, flatten and cause the vascular resistance to increase.

Finally, because the alveolar and extra-alveolar vessels are all part of the same vascular system, the resistance generated by the two groups of vessels is additive at any lung volume. The effect of changes in lung volume on the total pulmonary vascular resistance is a U-shaped curve (Figure 5–33). Thus, the pulmonary vascular resistance (PVR) is lowest near the functional residual capacity (FRC) and increases in response to both high and low lung volumes.

Blood Volume Changes. As blood volume increases, the recruitment and distention of pulmonary vessels will ensue, and pulmonary vascular resistance will tend to decrease (see Figure 5–30).

Blood Viscosity Changes. The viscosity of blood is derived from the hematocrit, the integrity of red blood cells, and the composition of plasma. As blood viscosity increases, the pulmonary vascular resistance increases. Table 5–4 summarizes the active and passive mechanisms of vascular resistance.

FIGURE 5-32 Schematic of the extra-alveolar "corner vessels" found at the junction of the alveolar septa. Expansion of the alveoli generates radial traction on the corner vessels, causing them to dilate. The alveolar vessels are compressed and flattened at high lung volumes.

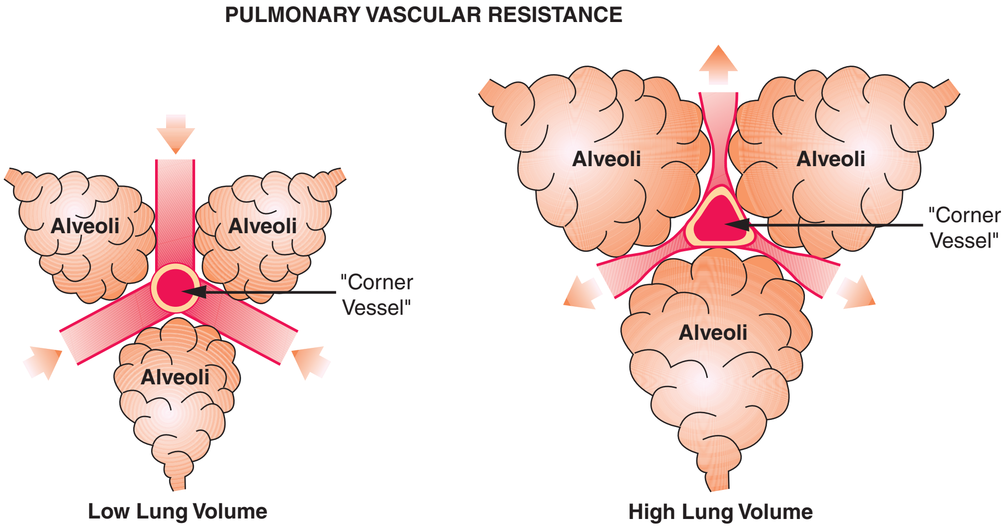

PULMONARY VASCULAR RESISTANCE
Alveoli
Alveoli
"Corner Vessel"
Alveoli
Low Lung Volume
Alveoli
Alveoli
"Corner Vessel"
Alveoli
High Lung Volume

FIGURE 5-33 At low lung volumes, the extra-alveolar vessels generate a greater resistance to pulmonary blood flow; at high lung volumes, the alveolar vessels generate a greater resistance to pulmonary blood flow. When added together, the resistances of the extra-alveolar and alveolar vessels demonstrate a U-shaped curve. Pulmonary vascular resistance (PVR) is lowest near the functional residual capacity (FRC) and increases at both high and low lung volumes. RV = residual volume; TLC = total lung capacity.

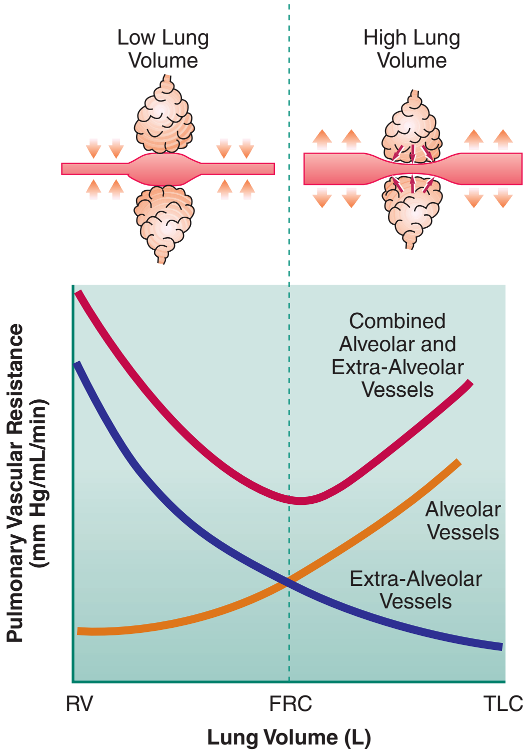


TABLE 5-4 Summary of the Effects of Active and Passive Mechanisms on Vascular Resistance

	↑Resistance (vascular constriction)	↓Resistance (vascular dilation)
ACTIVE MECHANISMS		
Abnormal Blood Gases		
↓P_{O_2}	X	
↑P_{CO_2}	X	
↓pH	X	
Pharmacologic Stimulation		
Epinephrine	X	
Norepinephrine	X	
Dobutamine	X	
Dopamine	X	
Phenylephrine	X	
Oxygen		X
Nitric oxide		X
Epoprostenol (Flolan)		X
Calcium-channel blocking agents		X
Pathologic Conditions		
Vessel blockage/obstruction	X	
Vessel wall disease	X	
Vessel destruction	X	
Vessel compression	X	
PASSIVE MECHANISMS		
↑Pulmonary arterial pressure		X
↑Left atrial pressure		X
↑Lung volume (extreme)	X	
↓Lung volume (extreme)	X	
↑Blood volume		X
↑Blood viscosity	X	

↑ = increased; ↓ = decreased.

Chapter Summary

The transport of oxygen from the lungs to the cells of the body and to transport carbon dioxide from the tissue cells to the lungs is a function of the circulatory system. The essential components of the circulatory system consist of the blood, the heart, and the pulmonary and systemic vascular systems. *Blood* consists of a variety of specialized cells called formed elements that are suspended in a fluid called *plasma*. The formed elements in the plasma are the red blood blood cells, white cells, and platelets. The white blood cells include the neutrophils, eosinophils, basophils, lymphocytes, and monocytes.

Essential components of the *heart* include the right and left atria, right and left ventricles, the interventricular septum, the pericardium, the walls of the heart (i.e., epicardium, myocardium, endocardium), the arterial supply of the heart (the left and right coronary artery), the venous drainage (i.e., the great cardiac veins, middle cardiac vein, coronary sinus, and thebesian veins), and the blood flow through the heart.

The *pulmonary* and *systemic vascular systems* are composed of the arteries, arterioles, capillaries, venules, and veins. The pulmonary arterioles and most of the arterioles in the systemic circulation are controlled by sympathetic impulses. Specialized stretch receptors called *baroreceptors* regulate the arterial blood pressure by initiating reflex adjustments to deviations in blood pressure.

The following three types of pressures are used to study the blood flow in the pulmonary and systemic vascular systems: intravascular, transmural, and driving. During each cardiac cycle, the ventricular systole and diastole have a direct relationship to the blood pressure. During ventricular systole, the arterial blood pressure sharply increases; during ventricular diastole, the arterial blood pressure decreases. The high and low blood pressures generated by ventricular systole and diastole result in mean intraluminal blood pressures throughout the pulmonary and systemic circulation. The mean systemic vascular pressure is about 10 times that of the pulmonary vascular system.

The distribution of pulmonary blood flow is a function of (1) gravity, (2) cardiac output, and (3) pulmonary vascular resistance. The influence of gravity in the upper right lung is described in terms of zones 1, 2, and 3; zone 3 is the most gravity-dependent area. Determinants of cardiac output are a function of ventricular preload, ventricular afterload, and myocardial contractility.

Finally, the pulmonary vascular resistance may increase or decrease as a result of active and passive mechanisms. Active mechanisms include abnormal blood gases, pharmacologic stimulation, and pathologic conditions. Passive mechanisms include increased pulmonary arterial pressure, increased left atrial pressure, lung volume changes, and blood volume and blood viscosity changes

Clinical connections associated with the topics discussed in this chapter include (1) anemia, (2) complete blood cell count, (3) pericarditis, (4) cardiac tamponade, (5) myocardial infarction—common diagnostic and treatment interventions of blocked coronary arteries, (6) carotid sinus massage, (7) a case study illustrating an automobile accident victim with massive blood loss, (8) congestive heart failure, (9) a case study illustrating left ventricular heart failure and pulmonary edema, (10) cor pulmonale, and (11) the cardiopulmonary hazards of positive-pressure ventilation.

1 Clinical Application Case

A 16-year-old girl was involved in an automobile accident on the way home from school during a freezing rain. As she drove over a bridge, her car hit a patch of ice, spun out of control, and hit a cement embankment. It took the emergency rescue team almost an hour to cut her out of her car with the "Jaws of Life." She was stabilized at the accident scene and then transported to the trauma center.

In the emergency department, the patient was unconscious and hypotensive. It was obvious that she had lost a lot of blood; her shirt and pants were soaked with blood. She had several large lacerations on her forehead, face, neck, left arm, and left leg. The patient's head was lowered, and her legs were elevated. The emergency department nurse started an intravenous infusion of Ringer's lactated solution. The respiratory therapist placed a nonrebreathing oxygen mask on the patient's face and drew an arterial blood sample. The radiologic technician took several portable X-rays.

The patient had several large bruises and abrasions over her left anterior chest that were most likely caused by the steering wheel when her car hit the cement embankment. Her four upper front teeth were broken off at the gum line. Her skin was pale and blue. Her vital signs were blood pressure—78/42 mm Hg, heart rate—145 beats/min and weak, and respirations—22 breaths/min and shallow. Her breath sounds were diminished bilaterally. Her arterial oxygen pressure (Pa_{O_2}) was 72 mm Hg.

Although chest X-ray showed no broken ribs, patches of pulmonary infiltrates (increased alveolar density) could be seen over the left anterior lung. Additional X-rays showed that she had a broken left humerus and left tibia. She was taken to surgery to repair her lacerations and broken bones. Five hours later, she was transferred to the surgical intensive care unit with her left arm and left leg in a cast.

To offset the increased alveolar density noted on the chest X-ray, the respiratory therapist administered continuous positive airway pressure (CPAP) via a face mask for 20 minutes every hour. Between the CPAP treatments, the patient continued to receive oxygen via a nonrebreathing mask. Two hours later, the patient was conscious and talking to her parents. Her skin appeared normal and her vital signs were blood pressure—115/82 mm Hg, heart rate—75 beats/min and strong, and respirations—14 breaths/min. Normal vesicular breath sounds were heard throughout both lungs. Her fractional concentration of inspired oxygen Fi_{O_2} was decreased to 0.4, and her Pa_{O_2} on this setting was 94 mm Hg.

The patient's cardiopulmonary status progressively improved and she was discharged on the sixth day of hospitalization. Although her broken bones healed

Clinical Application Case 1 (continued)

adequately, she had trouble walking normally for some time after the accident. Because of this problem, she continued to receive physical therapy twice a week for 6 months on an outpatient basis. At the time of her high school graduation, she had completely recovered.

Discussion

This case study illustrates (1) the activation of the baroreceptor reflex, (2) hypovolemia and how it relates to preload, (3) negative transmural pressure, and (4) the effects of gravity on blood flow.

As shown in this chapter, the specialized stretch receptors called *baroreceptors* (see Figure 5–18) regulate the arterial blood pressure by initiating reflex adjustments to changes in blood pressure. In this case, as the patient's blood pressure decreased from the loss of blood, neural impulses transmitted from the baroreceptors to the vasomotor and cardiac centers in the medulla decreased. This action, in turn, likely caused the patient's medulla to increase its sympathetic activity, which increased the heart rate (her pulse was 145 beats/min in the emergency department).

Because *ventricular preload* is a function of the blood pressure generated by the volume of blood returning to the left or right ventricle during diastole, it can easily be seen why the patient's ventricular preload decreased as she became hypovolemic from the loss of blood. In the emergency department, the fact that the patient's ventricular preload was low was reflected by her low blood pressure (78/42 mm Hg). It should be noted that as preload decreases, cardiac output decreases.

Finally, as the patient's preload decreased (from blood loss), the *transmural pressure* in her least gravity-dependent lung areas became increasingly negative. *Transmural pressure* is the difference between the intraluminal pressure of a vessel and the pressure surrounding the vessel (see Figure 5–20). The transmural pressure is negative when the pressure surrounding the vessel is greater than the pressure inside the vessel. In this case, this pathophysiologic process was offset by (1) lowering the patient's head and elevating her legs, which used the effects of gravity to move blood to the patient's lungs, and (2) replacing the volume of blood lost by administering Ringer's lactated solution. These two procedures worked to change the negative transmural pressures to positive transmural pressures in the lung regions.

2 Clinical Application Case

A 72-year-old woman presented in the intensive care unit with left ventricular heart failure and pulmonary edema (also called congestive heart failure). She had no history of respiratory disease. The patient's husband stated that she had gone to bed with no remarkable problems but awoke with severe dyspnea after several hours of sleep. Concerned, her husband called 911.

On observation, the patient's skin was cyanotic, and she was in obvious respiratory distress. Her neck veins were distended, and her ankles were swollen. Her vital signs were blood pressure—214/106 mm Hg, heart rate—90 beats/min, and respirations—28 breaths/min. On auscultation, course crackles were heard over both lung fields. She had a frequent, productive cough with frothy white secretions. Her arterial oxygen pressure (Pa_{O_2}) on 3 L/min oxygen via nasal cannula was 48 mm Hg. A portable chest X-ray showed dense, fluffy opacities (white areas) that spread outward from the hilar areas to the peripheral borders of the lungs. The chest X-ray also showed that the left ventricle was enlarged (ventricular hypertrophy).

The physician prescribed *positive inotropic agents* (refer to Table 15–3) to improve the strength of the left ventricular contraction and cardiac output and a systemic *vasodilator* (refer to Table 15–6) to decrease the patient's elevated blood pressure. Diuretic agents were also administered to promote fluid excretion. The respiratory therapist increased the patient's oxygen levels using a partial rebreathing mask.

(*continued*)

Clinical Application Case 2 (continued)

Two hours later, the patient's cardiopulmonary status had significantly improved. Her skin appeared normal and her neck veins were no longer distended. Her peripheral edema was no longer present. Her vital signs were blood pressure—130/87 mm Hg, heart rate—81 beats/min, and respirations—14 breaths/min. Her Pa_{O_2}, on 2 L/min oxygen via nasal cannula, was 103 mm Hg. A second chest X-ray showed that her lungs were clear and the left ventricle had returned to normal size.

Discussion

This case illustrates the effects of high blood pressure on (1) ventricular afterload, (2) ventricular contractility, (3) ventricular preload, and (4) transmural pressure.

Ventricular afterload is defined as the force against which the ventricles must work to pump blood. In this case, the patient's left ventricular afterload was very high because of increased peripheral vascular resistance. Clinically, this was reflected by the patient's high blood pressure of 214/106 mm Hg. Because of the high blood pressure and high left ventricular afterload, the patient's left ventricle eventually weakened and began to fail. As the ability of the left ventricle to pump blood decreased, the blood volume (and pressure) in the left ventricle increased. Even though the preload was increased, the left ventricle was unable to meet the increased demands created by the increased blood volume.

As this condition worsened, blood backed up into the patient's lungs, causing the *transmural pressure* in the pulmonary capillary to increase significantly. As a result of the excessively high transmural pressure, fluid leaked out of the pulmonary capillaries and into the alveoli and airways. Clinically, this was verified by the course crackles heard during auscultation, and by the white, frothy secretions produced when the patient coughed. As fluid accumulated in the patient's alveoli, the diffusion of oxygen into the pulmonary capillaries decreased. This was verified by the decreased Pa_{O_2} of 48 mm Hg.

Finally, as the blood volume and the transmural pressure in the pulmonary capillaries increased, the right ventricular afterload increased, which in turn decreased the ability of the right ventricle to pump blood despite the fact that the preload increased. This condition was reflected by the patient's distended neck veins and peripheral edema.

Fortunately, in this case the patient responded well to the positive inotropic vasodilator and diuretic agents. The vasodilator and diuretics worked to reduce the right and left ventricular afterloads, and the inotropic agents increased the ability of the ventricles to pump blood. The patient rapidly improved and was discharged on the fourth day of her hospital stay. Presently, she is seen by her family physician every 2 months.

Review Questions

1. Which of the following are granulocytes?

1. Neutrophils
2. Monocytes
3. Eosinophils
4. Lymphocytes
5. Basophils
   - A. 2 only
   - B. 5 only
   - C. 2 and 4 only
   - D. 1, 3, and 5 only

2. In healthy men, the hematocrit is about

- A. 25%
- B. 35%
- C. 45%
- D. 65%

3. Which of the following agents cause pulmonary vascular constriction?

1. Isoproterenol
2. Epinephrine
3. Oxygen
4. Dopamine
   - A. 3 only
   - B. 2 and 4 only
   - C. 1, 2, and 4 only
   - D. 1, 2, 3, and 4

4. If the pressure in the pulmonary artery is 34 mm Hg and the pressure in the left atrium is 9 mm Hg, what is the driving pressure?

A. 9 mm Hg
B. 17 mm Hg
C. 25 mm Hg
D. 34 mm Hg

5. The tricuspid valve lies between the

A. Right atrium and the right ventricle
B. Left ventricle and the aorta
C. Right ventricle and the pulmonary artery
D. Left atrium and the left ventricle

6. Which of the following is usually elevated in patients with asthma?

A. Lymphocytes
B. Neutrophils
C. Basophils
D. Eosinophils

7. The mean intraluminal pressure in the pulmonary capillaries is

A. 5 mm Hg
B. 10 mm Hg
C. 15 mm Hg
D. 20 mm Hg

8. An increase in the number of which of the following suggests a bacterial infection?

A. Lymphocytes
B. Neutrophils
C. Monocytes
D. Eosinophils

9. The force the ventricles must work against to pump blood is called

A. Myocardial contractility
B. Ventricular afterload
C. Negative inotropism
D. Ventricular preload

10. Compared with the systemic circulation, the pressure in the pulmonary circulation is about

A. $\frac{1}{10}$ the pressure
B. $\frac{1}{4}$ the pressure
C. $\frac{1}{3}$ the pressure
D. $\frac{1}{2}$ the pressure

11. The difference between the pressure in the lumen of a vessel and that of the pressure surrounding the vessel is called the

A. Driving pressure
B. Transmural pressure
C. Diastolic pressure
D. Intravascular pressure

12. Which of the following cause(s) pulmonary vasoconstriction?

1. Hypercapnia
2. Hypoxia
3. Acidemia
4. Increased H^+ concentration
    A. 3 only
    B. 2 and 4 only
    C. 2, 3, and 4 only
    D. 1, 2, 3, and 4

13. The cardioinhibitor center of the medulla slows the heart by sending neural impulses by way of the

1. Tenth cranial nerve
2. Parasympathetic nervous system
3. Sympathetic nervous system
4. Vagus nerve
    A. 4 only
    B. 3 only
    C. 1 and 4 only
    D. 1, 2, and 4 only

14. Which of the following cause(s) passive changes in the pulmonary vascular resistance?

1. pH changes
2. Transpulmonary pressure changes
3. P_{CO_2} changes
4. Blood viscosity changes
    A. 2 only
    B. 3 only
    C. 1 and 3 only
    D. 2 and 4 only

15. Which of the following cause blood clotting at a traumatized site?

A. Thrombocytes
B. Basophils
C. Monocytes
D. Eosinophils

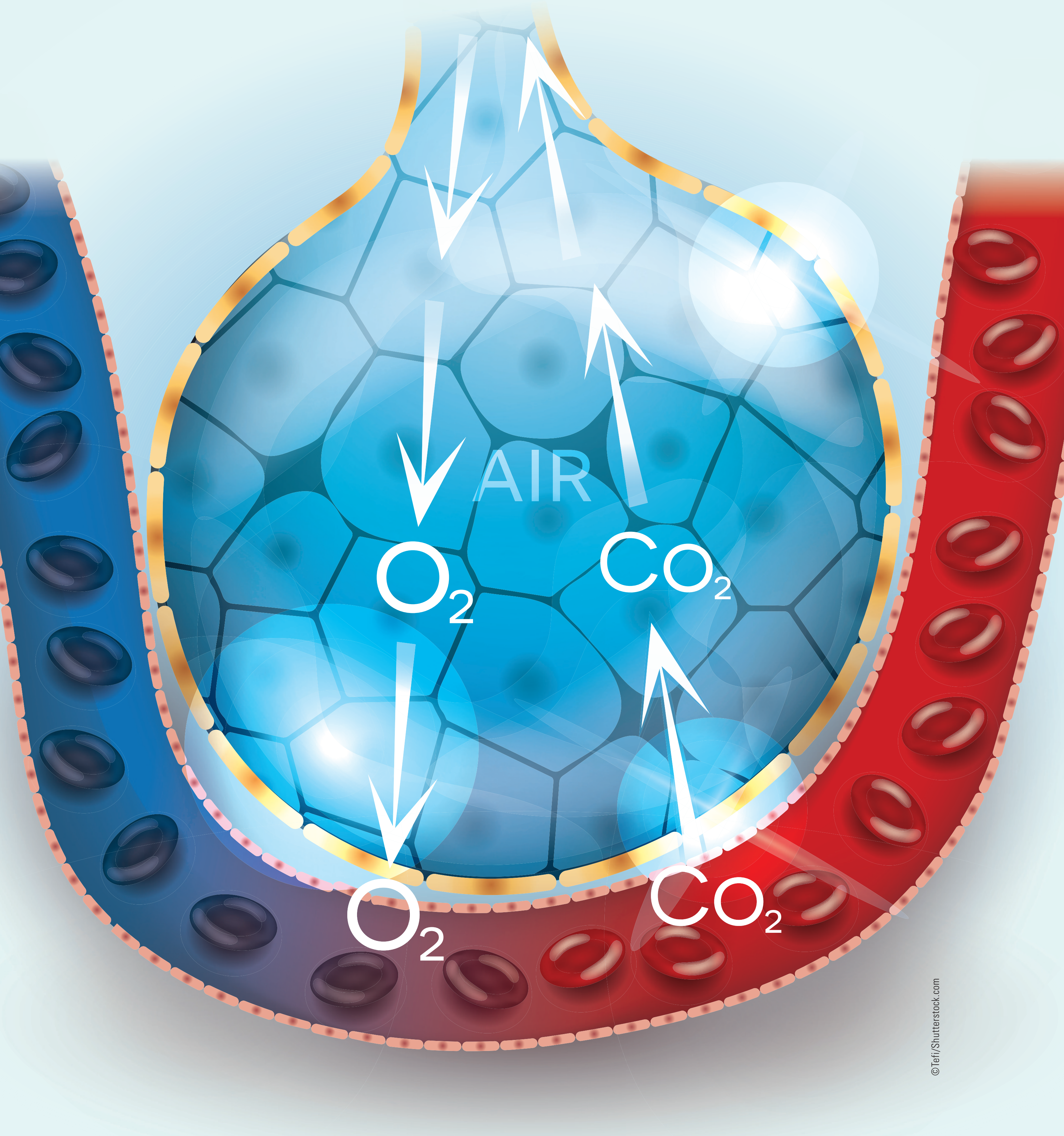
Clinical Application Questions

Case 1

1. As the patient's blood pressure decreased from the loss of blood, neural impulses transmitted from ____________________ to the vasomotor and cardiac centers in the medulla (decreased ________ ; increased ________).
2. In the emergency department, the patient's low preload was reflected by her low ________ .
3. As the preload decreases, the cardiac output ________________________________.
4. The negative transmural pressure in this case was offset by (1) ____________________ ____________________ and (2) ________ ________________________________ ________________________________

Case 2

1. In this case, the patient's left ventricular afterload was very high. This condition was reflected by the patient's ________________ .
2. As a result of the excessively high transmural pressure, fluid leaked out of the pulmonary capillaries and into the alveoli and airways. Clinically, this was verified by the ____________ and ____________ heard on auscultation.
3. As fluid accumulated in the patient's alveoli, the diffusion of oxygen into the pulmonary capillaries decreased. This was verified by the ________________________________ .
4. The increased right ventricular afterload was reflected by the patient's ________________.
5. The vasodilator and diuretic agents worked to reduce the right and left ventricular ________.


AIR
O_2
CO_2
O_2
CO_2

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CHAPTER 6

Oxygen and Carbon Dioxide Transport

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Calculate the quantity of oxygen that dissolves in the plasma of the blood.
2. Describe the major features of hemoglobin.
3. Calculate the quantity of oxygen that combines with hemoglobin.
4. Describe how the percentage of hemoglobin bound to oxygen, oxygen pressure, and oxygen content relate to the oxyhemoglobin dissociation curve.
5. Describe the clinical significance of the flat portion of the oxyhemoglobin dissociation curve.
6. Identify the factors that shift the oxyhemoglobin dissociation curve to the right.
7. Identify the factors that shift the oxyhemoglobin dissociation curve to the left.
8. Explain the clinical significance of a right or left shift of the oxyhemoglobin dissociation curve with regard to the loading of oxygen in the lungs and unloading of oxygen at the tissues.
9. Perform the following oxygen transport calculations: total oxygen delivery, arterial-venous oxygen content difference, oxygen consumption, oxygen extraction ratio, and mixed venous oxygen saturation.
10. Identify the factors that increase and decrease the oxygen transport calculations.
11. Differentiate between the forms of pulmonary shunting.
12. Describe the differences between hypoxemia and hypoxia.
13. Define the four main types of tissue hypoxia.
14. Explain the meaning of cyanosis.
15. List the three ways in which carbon dioxide is transported in the plasma.
16. List the three ways in which carbon dioxide is transported in the red blood cells.
17. Describe how carbon dioxide is converted to HCO_3^- at the tissue sites and then transported in the plasma to the lungs.
18. Explain how carbon dioxide is eliminated in the lungs.
19. Describe how the carbon dioxide dissociation curve differs from the oxyhemoglobin dissociation curve.
20. Explain how the Haldane effect relates to the carbon dioxide dissociation curve.

Introduction

An understanding of oxygen (O_2) and carbon dioxide (CO_2) transport is essential to the study of pulmonary physiology and to the clinical interpretation of arterial and venous blood gases (see Figure 6–1). Table 6–1

FIGURE 6-1 Radial-arterial blood gas stick. An arterial blood gas sample being obtained from a three-way stopcock, which is connected to an indwelling arterial catheter line. Common sites for indwelling arterial lines are the radial and brachial arteries.

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TABLE 6-1 Normal Blood Gas Value Ranges

Blood Gas Value*	Arterial	Venous
pH	7.35–7.45	7.30–7.40
P_{CO_2}	35–45 mm Hg (Pa_{CO_2})	42–48 mm Hg ($P\bar{v}_{CO_2}$)
HCO_3^-	22–28 mEq/L	24–30 mEq/L
P_{O_2}	80–100 mm Hg (Pa_{O_2})	35–45 mm Hg ($P\bar{v}_{O_2}$)

*Technically, only the oxygen (P_{O_2}) and carbon dioxide (P_{CO_2}) pressure readings are "true" blood gas values. The pH indicates the balance between the bases and acids in the blood. The bicarbonate (HCO_3^-) reading is an indirect measurement that is calculated from the pH and P_{CO_2} levels.

lists the normal blood gas values.[1,2] To fully understand this subject, the student must understand (1) how oxygen is transported from the lungs to the tissues, (2) the oxyhemoglobin dissociation curve and its clinical significance, (3) how various oxygen transport calculations are used to identify the patient's cardiac and ventilatory status, (4) the major forms of tissue hypoxia, and (5) how carbon dioxide is transported from the tissues to the lungs.

Oxygen Transport

The transport of oxygen between the lungs and the cells of the body is a function of the blood and the heart. Oxygen is carried in the blood in two forms: (1) as dissolved oxygen in the blood plasma and (2) chemically bound to the hemoglobin (Hb) that is encased in the erythrocytes or red blood cells (RBCs).

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[1] See Appendix V for a representative example of a cardiopulmonary profile sheet used to monitor the blood gas values of the critically ill patient.

[2] It should be noted that gas pressure values (e.g., P_{O_2}, P_{CO_2}, N_2) may be described as either mm Hg or torr. *Torr* was named after Evangelista Torricelli, an Italian physicist and mathematician, who discovered the principle of the mercury barometer in 1644. In honor of Torricelli, the torr was defined as a unit of pressure equal to 1 mm Hg—i.e., 1 torr = 1 mm Hg. Blood pressure values and barometric pressure (i.e., atmospheric pressure) are always expressed in mm Hg.

Oxygen Dissolved in the Blood Plasma

As oxygen diffuses from the alveoli into the pulmonary capillary blood, it dissolves in the plasma of the blood. The term **dissolve** means that when a gas like oxygen enters the plasma, it maintains its precise molecular structure (in this case, O_2) and moves freely throughout the plasma in its normal gaseous state. Clinically, it is this portion of the oxygen that is measured to assess the patient's partial pressure of oxygen (P_{O_2}) (see Table 6–1).

The quantity of oxygen that dissolves in the plasma is a function of Henry's law, which states that the amount of gas that dissolves in a liquid (in this case, plasma) at a given temperature is proportional to the partial pressure of the gas. At normal body temperature, about 0.003 mL of oxygen will dissolve in 100 mL of blood for every 1 mm Hg of P_{O_2}. The oxygen content in the blood is expressed in milliliters of O_2 per 100 mL of blood—and is written as milliliters of O_2 per deciliter[3] (mL/dL).

Thus, in the healthy individual with an arterial oxygen partial pressure (Pa_{O_2}) of 100 mm Hg, approximately 0.3 mL of oxygen is dissolved in every 100 mL of plasma (0.003×100 mm Hg $= 0.3$ mL/dL). Or, in the individual with a PaO_2 200 mm Hg, about 0.6 mL of oxygen is dissolved in each deciliter of plasma (0.003×200 mm Hg $= 0.6$ mL/dL). In terms of total oxygen transport, a relatively small percentage of oxygen is transported in the form of dissolved oxygen.

Oxygen Bound to Hemoglobin

Hemoglobin

Most of the oxygen that diffuses into the pulmonary capillary blood rapidly moves into the RBCs and chemically attaches to the hemoglobin. Each RBC contains approximately 280 million hemoglobin molecules, which are highly specialized to transport oxygen and carbon dioxide.

Normal adult hemoglobin, which is designated Hb A, consists of (1) four heme groups, which are the pigmented, iron-containing nonprotein portions of the hemoglobin molecule, and (2) four amino acid chains (polypeptide chains) that collectively constitute globin (a protein) (Figure 6–2).

At the center of each heme group, the iron molecule can combine with one oxygen molecule in an easily reversible reaction to form oxyhemoglobin:

Hb	+	O_2	$\rightleftharpoons$	Hb_{O_2}
Reduced hemoglobin (uncombined or deoxygenated hemoglobin)		Oxygen		Oxyhemoglobin (combined or oxygenated hemoglobin)

Because there are four heme/iron groups in each Hb molecule, a total of four oxygen molecules can combine with each Hb molecule. When four oxygen molecules are bound to one Hb molecule, the Hb is said to be 100 percent saturated with oxygen; an Hb molecule with three oxygen molecules is 75 percent saturated; and so forth. Hemoglobin bound with oxygen (Hb_{O_2}) is called **oxyhemoglobin**. Hemoglobin not bound with oxygen (Hb) is called **reduced hemoglobin** or **deoxyhemoglobin**. The amount of oxygen bound to Hb is directly related to the partial pressure of oxygen.

The globin portion of each Hb molecule consists of two identical alpha (α) chains, each with 141 amino acids, and two identical beta (β) chains, each with 146 amino acids ($\alpha_2\beta_2$). Normal fetal hemoglobin (Hb F) has two alpha (α) chains and two gamma (γ) chains ($\alpha_2\gamma_2$). This increases hemoglobin's attraction to oxygen and facilitates transfer of maternal oxygen across the placenta. Fetal hemoglobin is gradually replaced with Hb A over the first year of postnatal life.

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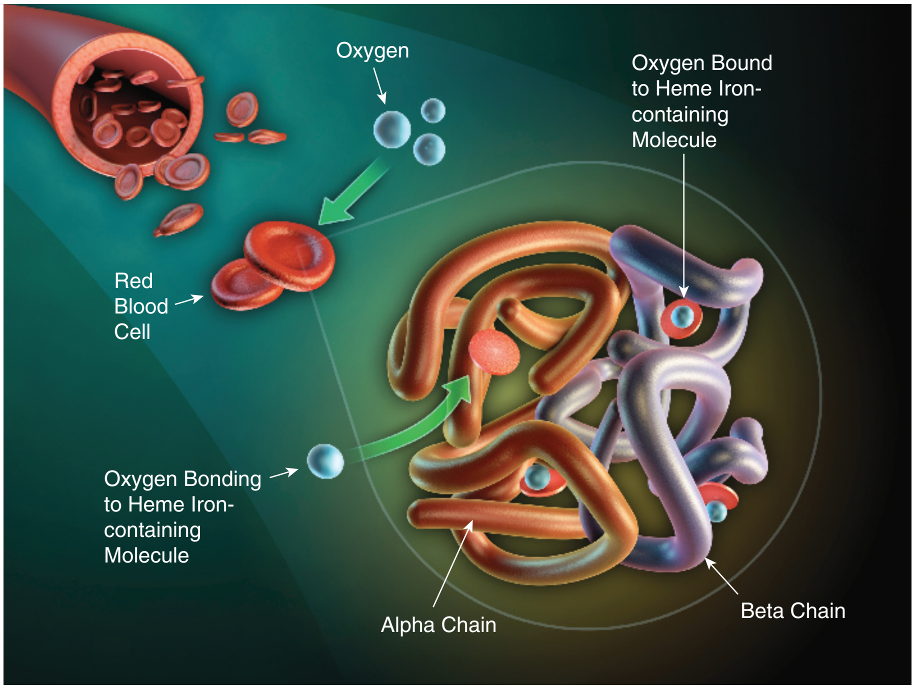
[3] Deciliter is defined as a metric unit of capacity, equal to 1/10 (0.1) L (about 3.38 fluid ounces).

FIGURE 6-2 Schematic of a hemoglobin molecule. The globin (protein) portion consists of two identical alpha (α) chains and two beta (β) chains. The four heme (iron-containing) portions are in the center of each globin molecule.


Oxygen
Oxygen Bound to Heme Iron-containing Molecule
Red Blood Cell
Oxygen Bonding to Heme Iron-containing Molecule
Alpha Chain
Beta Chain

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When the precise number, sequence, or spatial arrangement of the globin amino acid chains is altered, the hemoglobin will be abnormal. For example, sickle cell hemoglobin (Hb S) has a different amino acid substituted into the β chain. This causes the deoxygenated hemoglobin molecule (hemoglobin not bound to oxygen) to change the RBC shape from biconcave to a crescent or sickle form that has a tendency to form thrombi (clots). Various drugs and chemicals, such as nitrites, can change the iron molecule in the heme from the *ferrous state* to the *ferric state,* eliminating the ability of hemoglobin to transport oxygen. This type of hemoglobin is known as *methemoglobin.*

The normal hemoglobin value for the adult male is 14 to 16 g per100 mL of blood. In other words, if all the hemoglobin were to be extracted from all the RBCs in 100 mL of blood, the hemoglobin would actually weigh between 14 and 16 g. Clinically, the weight measurement of hemoglobin, in reference to 100 mL of blood, is referred to as *grams per deciliter* (g/dL). The average adult female hemoglobin value is 12 to 15 g/dL. The average infant hemoglobin value is 14 to 20 g/dL. Hemoglobin constitutes about 33 percent of the RBC weight.

Quantity of Oxygen Bound to Hemoglobin

Under normal conditions, each g/dL is capable of carrying approximately 1.34 mL[4] of oxygen. Thus, if the hemoglobin level is 15 g/dL, and if hemoglobin is fully saturated, about 20.1 mL/dL of oxygen will be bound to hemoglobin. The 20.1 value is calculated using the following formula:

$$\begin{aligned} O_2 \text{ bound to Hb} &= 1.34 \text{ mL } O_2 \times 15 \text{ g/dL Hb} \\ &= 20.1 \text{ mL/dL } O_2 \end{aligned}$$

---

[4] The literature also reports values of 1.36, 1.38, and 1.39. The figure 1.34 is the most commonly used factor and is used in this textbook.

Clinical Connection 6-1

Case Study—The Importance of Hemoglobin in Oxygen Transport

In the Clinical Application Case 1 (page 303), the respiratory therapist is called to assist in the care of a 12-year-old female victim of a drive-by shooting. This case demonstrates the importance of hemoglobin in the transport of oxygen. As a result of the gunshot wound to the chest, the patient has a significant amount of blood loss—causing the patient to lose consciousness, become cyanotic, and be damp to the touch. Even though the patient's Pa_{O_2} is very high in the emergency department (>500 mm Hg), her tissue oxygenation is seriously impaired because of a very low Hb concentration (4 g/dL). This case nicely illustrates how the Pa_{O_2} and Sa_{O_2} can be very misleading—and dangerous—when the hemoglobin level is not entered into the patient's oxygen transport calculations. Note that a unit of "life-saving" blood was started immediately on the patient's arrival in the emergency department.

At a normal arterial oxygen pressure (Pa_{O_2}) of 100 mm Hg, however, the hemoglobin saturation (Sa_{O_2}) is only about 97 percent because of these normal physiologic shunts:

- Thebesian venous drainage into the left atrium
- Bronchial venous drainage into the pulmonary veins
- Alveoli that are underventilated relative to pulmonary blood flow

Thus, the amount of arterial oxygen in the preceding equation must be adjusted to 97 percent. The equation is written as follows:

$$\begin{array}{l} 20.1\ \text{mL/dL } O_2 \\ \times 0.97 \\ \hline 19.5\ \text{mL/dL } O_2 \end{array}$$

Total Oxygen Content

To determine the total amount of oxygen in 100 mL of blood, the dissolved oxygen and the oxygen bound to hemoglobin must be added together. The following case study summarizes the calculations required to compute an individual's total oxygen content.

Case Study: Anemic Patient

A 27-year-old woman with a long history of anemia (decreased hemoglobin concentration) is showing signs of respiratory distress. Her respiratory rate is 36 breaths/min, heart rate 130 beats/min, and blood pressure 155/90 mm Hg. Her hemoglobin concentration is 6 g/dL, and her Pa_{O_2} is 80 mm Hg (Sa_{O_2} 90%).

Based on this information, the patient's total oxygen content is computed as follows:

1. **Dissolved O_2**

$$\begin{array}{l} 80\ Pa_{O_2} \\ \times 0.003\ (\text{dissolved } O_2 \text{ factor}) \\ \hline 0.24\ \text{mL/dL } O_2 \end{array}$$

2. **Oxygen bound to hemoglobin**

$$\begin{array}{l} 6 \text{ g/dL H} \\ \underline{\times 1.34 \text{ (}O_2\text{ bound to Hb factor)}} \\ 8.04 \text{ mL/dL } O_2 \text{ (at } Sa_{O_2} \text{ of 100\%)} \end{array}$$

$$\begin{array}{l} 8.04 \text{ mL/dL } O_2 \\ \underline{\times 0.90\ Sa_{O2}} \\ 7.236 \text{ mL/dL } O_2 \end{array}$$

3. **Total oxygen content**

$$\begin{array}{l} 7.236 \text{ mL/dL } O_2 \text{ (bound to hemoglobin)} \\ \underline{+\ 0.24 \text{ mL/dL } O_2 \text{ (dissolved } O_2\text{)}} \\ 7.476 \text{ mL/dL } O_2 \text{ (total amount of } O_2\text{/100 mL of blood)} \end{array}$$

Note that the patient's total arterial oxygen content is less than 50 percent of normal. Her hemoglobin concentration, which is the primary mechanism for transporting oxygen, is very low. Once this problem is corrected, the clinical manifestations of respiratory distress should no longer be present.

The total oxygen content of the arterial blood (Ca_{O_2}), mixed venous blood ($C\bar{v}_{O_2}$), and pulmonary capillary blood (Cc_{O_2}) is calculated as follows:

- Ca_{O_2}: Oxygen content of arterial blood
  ($Hb \times 1.34 \times Sa_{O_2}$) + ($Pa_{O_2} \times 0.003$)
- $C\bar{v}_{O_2}$: Oxygen content of mixed venous blood
  ($Hb \times 1.34 \times S\bar{v}_{O_2}$) + ($P\bar{v}_{O_2} \times 0.003$)
- Cc_{O_2}: Oxygen content of pulmonary capillary blood
  ($Hb \times 1.34$)[5] + ($P_{A_{O_2}}$[6] $\times 0.003$)

Clinical Connection 6-2

Polycythemia

An abnormally high red blood cell (RBC) count is known as **polycythemia**. It commonly occurs when the bone marrow is stimulated to make more RBCs in response to chronically low arterial blood oxygen levels—which is referred to as **secondary polycythemia**. Polycythemia helps to offset the adverse effects of a chronically low oxygen level in the blood by increasing the oxygen-carrying capacity of the blood.

The hallmark of polycythemia is an elevated hematocrit or hemoglobin. Polycythemia is identified when the hematocrit is greater than 52 percent in men (normal: 45 percent) and 48 percent in women (normal: 42 percent). When using the hemoglobin level, polycythemia is present when the hemoglobin level is greater than 18.5 g/dL in men (normal: 14 to 16 g/dL), and 16.5 g/dL in women (normal: 12 to 15 g/dL).

The respiratory therapist will frequently treat patients with polycythemia who are suffering from chronically low P_{O_2} levels caused by chronic pulmonary disorders—such as emphysema, bronchitis, and cystic fibrosis. For example, consider the following representative case study of a typical patient with polycythemia.

Case Study: COPD Patient with Polycythemia

A 71-year-old male with a long history of emphysema and chronic bronchitis (COPD) enters the hospital for a routine evaluation. The patient is well known to

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[5] It is assumed that the hemoglobin saturation with oxygen in the pulmonary capillary blood (Sc_{O_2}) is 100 percent or 1.0.

[6] Refer to the section "The Ideal Alveolar Gas Equation" in Chapter 4.

Clinical Connection 6-2, Continued

the respiratory care team. He has a 45-year history of smoking two packs of cigarettes a day. He has a history of high blood pressure and a number of episodes of congestive heart failure. Inspection reveals a barrel chest, clubbing of the fingers and toes, cyanotic skin, and pitting edema around the ankles. He is experiencing pursed-lip breathing, and he is using his accessory muscles of respiration. Vital signs are: blood pressure, 135/90; heart rate, 85 bpm; respiratory rate, 10/min; and oral temperature, 37°C (98.6°F).

On room air, the patient's Pa_{O_2} is 45 mm Hg and the Sa_{O_2} is 75 percent. The patient's CBCs reveal an Hb level of 19 g/dL. When evaluating the patient's Pa_{O_2} and Sa_{O_2} values, the oxygenation status appears severely low. However, when the patient's total oxygen content is computed—with an Hb level of 19 g/dL—the patient's total oxygen delivery status is actually quite good—see the following calculation:

1. **Dissolved O_2**

$$\begin{array}{l} 45\ Pa_{O_2} \\ \times\ 0.003\ (\text{dissolved } O_2 \text{ factor}) \\ \hline 0.135 \end{array}$$

2. **Oxygen bound to hemoglobin**

$$\begin{array}{l} 19\ \text{g/dL Hg} \\ \times\ 1.34\ (O_2 \text{ bound to Hb factor}) \\ \hline 25.46\ \text{mL/dL } O_2\ (\text{at } Sa_{O_2} \text{ of } 100\%) \end{array}$$

$$\begin{array}{l} 25.46\ \text{mL/dL } O_2 \\ \times\ 0.75\ Sa_{O_2} \\ \hline 19.095\ \text{mL/dL } O_2 \end{array}$$

3. **Total oxygen content**

$$\begin{array}{l} 19.095\ \text{mL/dL (bound to hemoglobin)} \\ +\ 0.135\ \text{mL/dL (dissolved } O_2) \\ \hline 19.23\ \text{mL/dL } O_2\ (\text{total amount of } O_2/100 \text{ mL of blood}) \end{array}$$

Note that the patient's "total arterial oxygen content" is normal (19.23 mL/dL O_2)—in spite of the fact the Pa_{O_2} is only 45 mm Hg. This is because the patient's hemoglobin concentration, which is one of the major mechanisms for transporting oxygen, is very high: The patient has polycythemia.

Unfortunately, the advantage of the increased oxygen-carrying capacity in polycythemia is often offset by the increased viscosity of the blood when the hematocrit reaches about 55 to 60 percent. Because of the increased viscosity of the blood, a greater driving pressure is needed to maintain a given flow. The work on the right and left ventricle must increase in order to generate the pressure needed to overcome the increased viscosity. This can ultimately lead to left ventricular hypertrophy and failure and to right ventricular hypertrophy and cor pulmonale. The general clinical manifestations of polycythemia include weakness and fatigue, headaches, lightheadedness, and dizziness, digital clubbing, and low Pa_{O_2} levels.

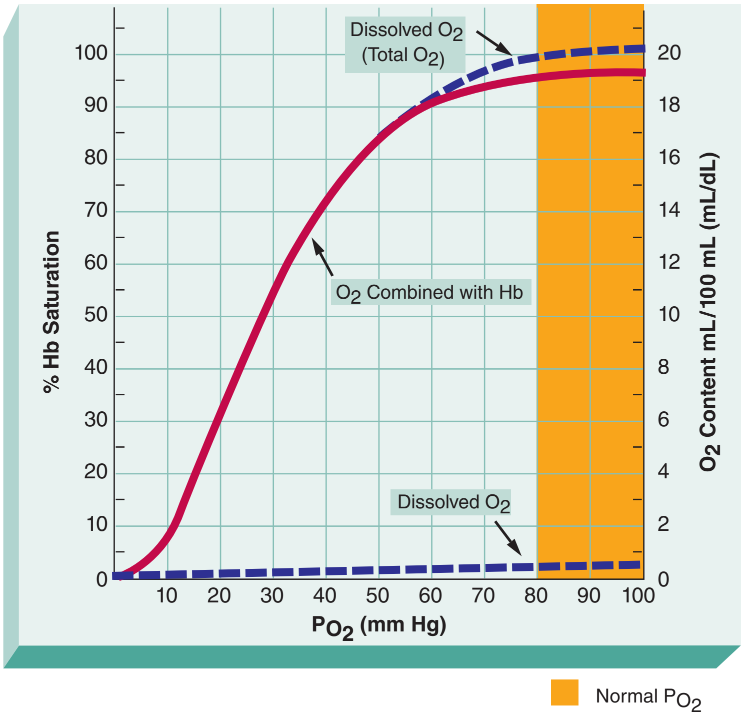
It will be shown later in this chapter how various mathematical manipulations of the Ca_{O_2}, $C\bar{v}_{O_2}$, and Cc_{O_2} values are used in different oxygen transport calculations to reflect important factors concerning the patient's cardiac and ventilatory status.

Oxyhemoglobin Dissociation Curve

As shown in Figure 6–3, the **oxyhemoglobin dissociation curve** (Hb_{O_2} curve), also known as the **oxyhemoglobin equilibrium curve**, is part of a nomogram that graphically illustrates the *percentage of hemoglobin* (left-hand side of the graph) that is chemically bound to oxygen at each *oxygen pressure* (bottom portion of the graph). On the right-hand side of the graph, a second scale is included that gives the precise *oxygen content* that is carried by the hemoglobin at each oxygen pressure.

The curve is S-shaped with a steep slope between 10 and 60 mm Hg and a flat portion between 70 and 100 mm Hg. The steep portion of the curve shows that oxygen rapidly combines with hemoglobin as the P_{O_2} increases. Beyond this point (60 mm Hg), a further increase in the P_{O_2} produces only a slight increase

FIGURE 6–3 Oxyhemoglobin dissociation curve.



in oxygen-hemoglobin bonding. In fact, because the hemoglobin is already 90 percent saturated at a P_{O_2} of 60 mm Hg, an increase in the P_{O_2} from 60 to 100 mm Hg elevates the total saturation of the hemoglobin by only 7 percent (see Figure 6–3).

Clinical Significance of the Flat Portion of the Curve

The P_{O_2} can fall from 100 to 60 mm Hg and the hemoglobin will still be 90 percent saturated with oxygen. Thus, the upper curve plateau illustrates that hemoglobin has an excellent safety zone for the loading of oxygen in the lungs.

As the hemoglobin moves through the alveolar-capillary system to pick up oxygen, a significant partial pressure difference continues to exist between the alveolar gas and the blood, even after most of the oxygen is transferred. This mechanism enhances the diffusion of oxygen during the transit time of the hemoglobin in the alveolar-capillary system.

The flat portion also means that increasing the P_{O_2} beyond 100 mm Hg adds very little additional oxygen to the blood. In fact, once the P_{O_2} increases enough to saturate 100 percent of the hemoglobin with oxygen, the hemoglobin will no longer accept any additional oxygen molecules. However, a small additional amount of oxygen continues to dissolve in the plasma as the P_{O_2} rises ($P_{O_2} \times 0.003 =$ dissolved P_{O_2}).

Clinical Significance of the Steep Portion of the Curve

A reduction of P_{O_2} to below 60 mm Hg produces a rapid decrease in the amount of oxygen bound to hemoglobin. Clinically, therefore, when the P_{O_2} continues to fall below 60 mm Hg, the quantity of oxygen delivered to the tissue cells may be significantly reduced.

The steep portion of the curve also shows that as the hemoglobin moves through the capillaries of the tissue cells, a large amount of oxygen is released from the hemoglobin for only a small decrease in P_{O_2}. Thus, the diffusion of oxygen from the hemoglobin to the tissue cells is enhanced.

Clinical Connection 6-3

The Pulse Oximeter—The Pa_{O_2} and Sa_{O_2} Relationship

The **pulse oximeter** is a clip-like medical device that indirectly monitors the patient's arterial oxyhemoglobin saturation (see Figure 6-4). When a pulse oximeter is used, the oxygen saturation value is reported as Sp_{O_2} (the "p" represents pulse)—as opposed to measuring the oxygen saturation directly by means of an arterial blood gas sample, which is reported as Sa_{O_2} (the "a" represents direct arterial blood).

The pulse oximeter measures oxygen saturation by reflecting light off the hemoglobin. The color change in hemoglobin is directly related to its oxygen saturation. To prevent measuring capillary or venous blood, the oximeter assesses only the pulsing waveforms. The pulse oximeter is easily connected to the patient's fingertip, toe, or ear lobe. Most monitors also display the pulse rate. The pulse oximeter is routinely used to follow a patient's oxygen saturation trends—and, importantly, to identify potentially dangerous drops in the patient's partial pressure of arterial oxygenation (Pa_{O_2}) status.

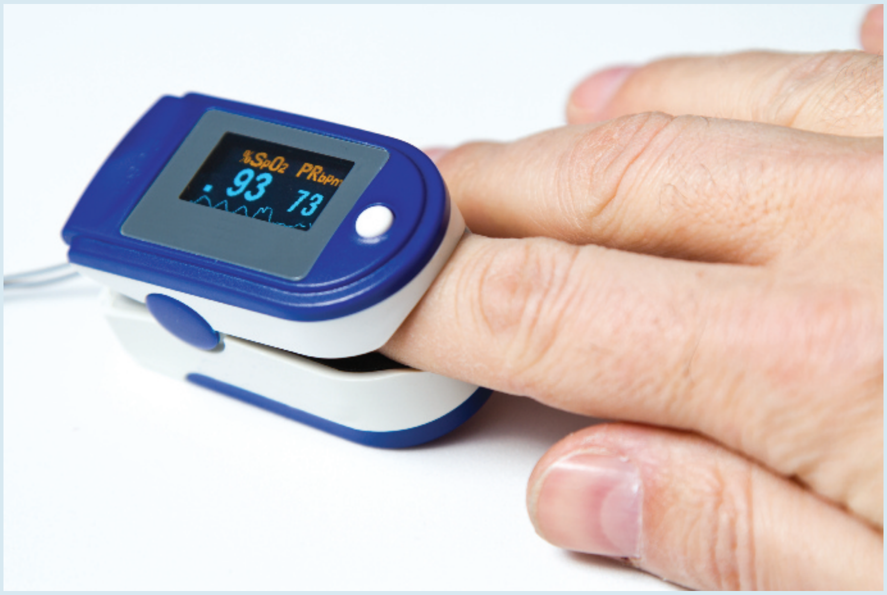
For example, by using the general rule of thumb called the **40-50-60/70-80-90 Pa_{O_2}/Sa_{O_2} rule** in the following box, the patient's Sa_{O_2} value can readily provide a good estimate of the patient's Pa_{O_2} value.

The 40-50-60/70-80-90 Rule (General Pa_{O_2}/Sa_{O_2} Relationship)

Approximate Pa_{O_2} (mm Hg)	Approximate Sa_{O_2} (%)
40	70
50	80
60	90

Thus, if a patient's pulse oximeter reading is 90 percent or greater, the patient should have a Pa_{O_2} of 60 mm Hg or greater. It should be stressed, however, that this rule is only a general guideline. The 40-50-60/70-80-90 rule works best when (1) the pH, Pa_{CO_2}, and Hb values are within the normal range, and (2) the patient's Pa_{O_2} value is on the steep portion of the oxyhemoglobin dissociation curve (see Figure 6-3). Whenever the respiratory therapist suspects the patient's oxygenation status is moving in a harmful direction, an arterial blood gas should be performed to fully evaluate the patient's pH, Pa_{CO_2}, HCO_3^-, Pa_{O_2}, and Sa_{O_2} values. Most pulse oximeter measurements below 70 percent are considered inaccurate and unreliable.

FIGURE 6-4 A pulse oximeter.



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The P_{50}

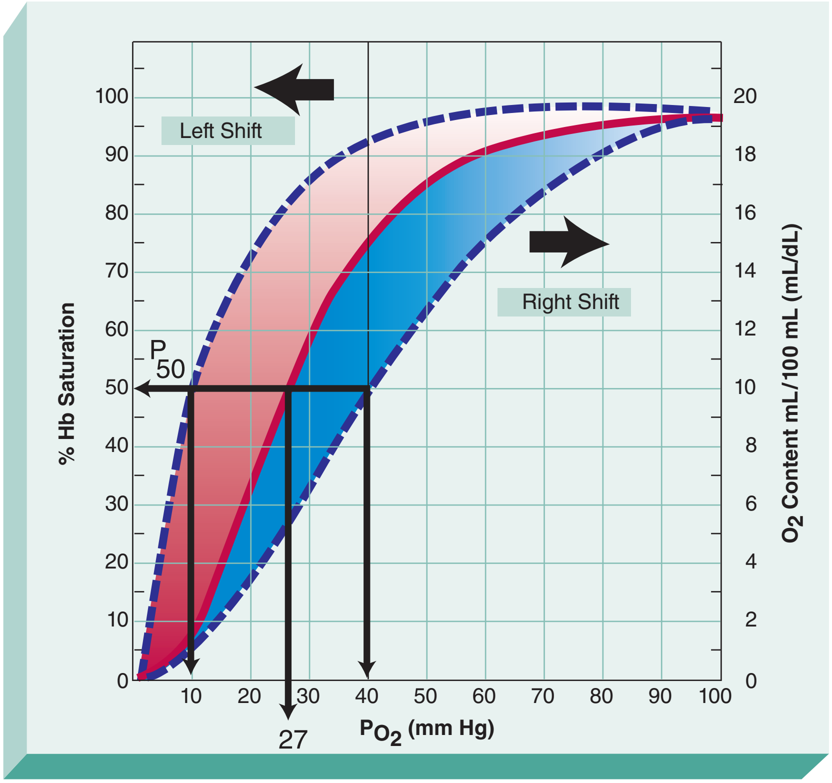
A point of reference on the oxyhemoglobin dissociation curve is the P_{50} (Figure 6–5). The P_{50} represents the partial pressure at which the hemoglobin is 50 percent saturated with oxygen—that is, when there are two oxygen molecules on each hemoglobin molecule. Normally, the P_{50} is about 27 mm Hg. Clinically, however, there are a variety of abnormal conditions that can shift the oxyhemoglobin dissociation curve to either the right or left. When this happens, the P_{50} changes. For example, when the curve shifts to the right, the affinity of hemoglobin for oxygen decreases, causing the hemoglobin to be less saturated at a given P_{O_2}. Thus, *when the curve shifts to the right, the* P_{50} *increases.* On the other hand, when the curve moves to the left, the affinity of hemoglobin for oxygen increases, causing the hemoglobin to be more saturated at a given P_{O_2}. Thus, *when the curve shifts to the left, the* P_{50} *decreases* (see Figure 6–5).

Factors That Shift the Oxyhemoglobin Dissociation Curve

pH

As the blood hydrogen ion concentration increases (decreased pH), the oxyhemoglobin dissociation curve shifts to the right. This mechanism enhances the unloading of oxygen at the cellular level because the pH decreases in this area as carbon dioxide (the acidic end-product of cellular metabolism) moves into the blood. In contrast, as the blood hydrogen ion (H^+) concentration decreases, the curve shifts to the left. This mechanism facilitates the loading of oxygen onto hemoglobin as blood passes through the lungs because the pH increases as carbon dioxide moves out of the blood and into the alveoli.

FIGURE 6-5 The P_{50} represents the partial pressure at which hemoglobin is 50 percent saturated with oxygen. When the oxyhemoglobin dissociation curve shifts to the right, the P_{50} increases. When the oxyhemoglobin dissociation curve shifts to the left, the P_{50} decreases.



Temperature

As the body temperature increases, the curve moves to the right. Thus, exercise, which produces an elevated temperature, enhances the release of oxygen as blood flows through the muscle capillaries. Conversely, as the body temperature decreases, the curve shifts to the left. This mechanism explains—in part—why an individual's lips, ears, and fingers appear blue while swimming in very cold water.[7] That is, their Pa_{O_2} is normal, but oxygen is not readily released from the hemoglobin at the cold tissue sites.

Carbon Dioxide

As the P_{CO_2} level increases (increased H^+ concentration), the oxyhemoglobin saturation decreases, shifting the oxyhemoglobin dissociation curve to the right, whereas decreasing Pa_{O_2} levels (decreased H^+ concentrations) shift the curve to the left. The effect of Pa_{O_2} and pH on the oxyhemoglobin curve is known as the **Bohr effect**. The Bohr effect is most active in the capillaries of working muscles, particularly the myocardium.

2,3-Biphosphoglycerate (formerly called 2,3-Diphosphoglycerate)

The RBCs contain a large quantity (about 15 mol/g Hb) of the substance 2,3-biphosphoglycerate (2,3-BPG). 2,3-BPG is a metabolic intermediary that is formed by the RBCs during anaerobic glycolysis. Hemoglobin's affinity for oxygen decreases as the 2,3-BPG level increases. Thus, the effect of an elevated concentration of 2,3-BPG is to shift the oxyhemoglobin dissociation curve to the right. Clinically, a variety of conditions affect the level of 2,3-BPG.

- **Hypoxia.** Regardless of the cause, hypoxia increases the 2,3-BPG level.
- **Anemia.** The 2,3-BPG level increases as the hemoglobin concentration decreases. This mechanism may explain why individuals with anemia frequently do not manifest the signs or symptoms associated with hypoxia.
- **pH changes.** As the pH increases, the 2,3-BPG concentration increases. Thus, the shift of the oxyhemoglobin dissociation curve to the left by the increased pH is offset somewhat by the increased 2,3-BPG level, which shifts the curve to the right. Conversely, as the pH decreases, the 2,3-BPG concentration decreases. Thus, while the decreased pH shifts the curve to the right, the decreased 2,3-BPG level works to shift the curve to the left.
- **Stored blood.** Blood stored for as little as 1 week has been shown to have very low concentrations of 2,3-BPG. Thus, when patients receive stored blood, the oxygen unloading in their tissues may be reduced because of the decreased 2,3-BPG level.

Fetal Hemoglobin

Fetal hemoglobin (Hb F) is chemically different from adult hemoglobin. Hb F has a greater affinity for oxygen and, therefore, shifts the oxyhemoglobin dissociation curve to the left (reducing the P_{50}). During fetal development, the higher affinity of Hb F enhances the transfer of oxygen from maternal blood to fetal blood. After birth, Hb F progressively disappears and is completely absent after about 1 year.

Carbon Monoxide

Carbon monoxide (CO) has about 210 times the affinity of oxygen for hemoglobin. Because of this, a small amount of CO can tie up a large amount of hemoglobin and, as a result, prevent oxygen molecules from bonding to hemoglobin. When CO bonds with hemoglobin it is called **carboxyhemoglobin (CO_{Hb})**.

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[7] It should also be noted that hypothermia can cause peripheral vasoconstriction to conserve body heat. This action can also contribute to the reason lips, ears, and fingers often appear blue in the cold.

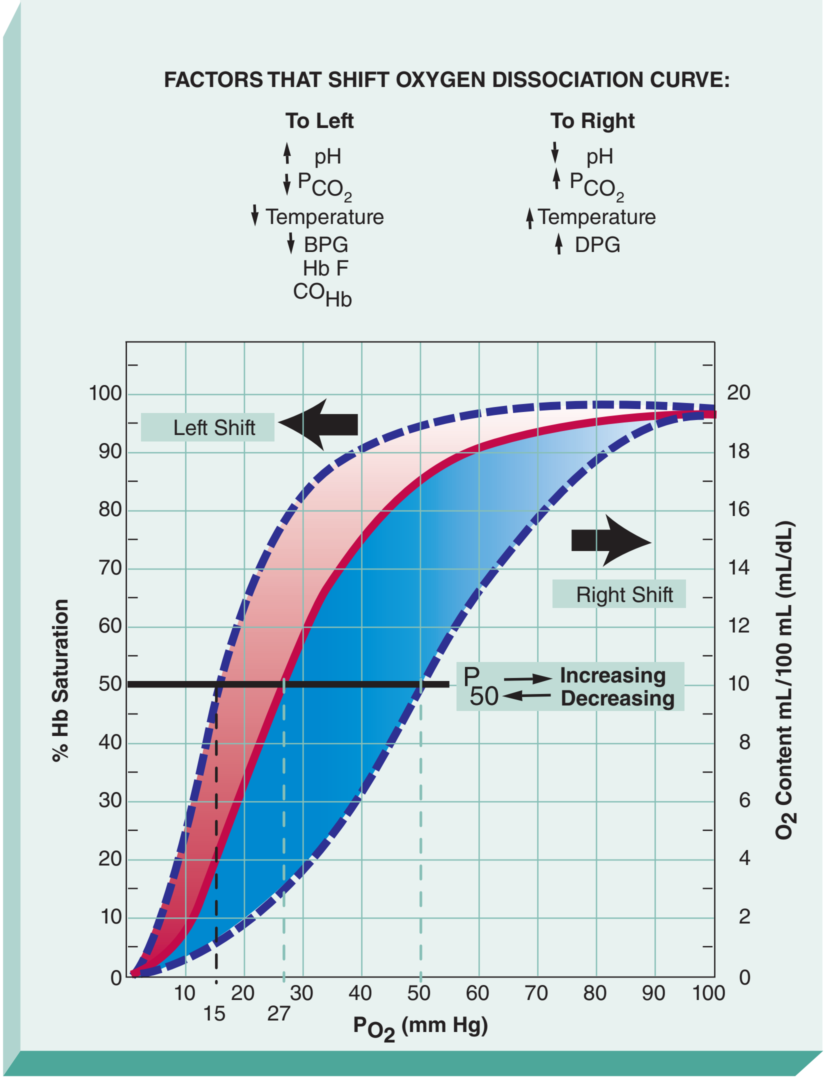
CO_{Hb} can seriously reduce the amount of oxygen transferred to the tissue cells. In addition, when CO_{Hb} is present, the affinity of hemoglobin for oxygen increases and shifts the oxyhemoglobin dissociation curve to the left. Thus, the oxygen molecules that do manage to combine with hemoglobin are unable to unload easily in the tissues.

Figure 6–6 summarizes factors that shift the oxyhemoglobin dissociation curve to the right and left and how the P_{50} is affected by these shifts.

Clinical Significance of Shifts in the Oxyhemoglobin Dissociation Curve

When an individual's blood Pa_{O_2} is within normal limits (80 to 100 mm Hg), a shift of the oxyhemoglobin dissociation curve to the right or left does not significantly affect hemoglobin's ability to transport oxygen to the peripheral tissues because shifts in this pressure range (80 to 100 mm Hg) occur on the flat portion

FIGURE 6-6 Factors that shift the oxyhemoglobin dissociation curve to the right and left. (BPG = 2,3-biphosphoglycerate; for other abbreviations, see text.)



of the curve. However, when an individual's blood Pa_{O_2} falls below the normal range, a shift to the right or left can have a remarkable effect on the hemoglobin's ability to pick up and release oxygen because shifts below the normal pressure range occur on the steep portion of the curve. For example, consider the loading and unloading of oxygen during the clinical conditions discussed next.

Right Shifts—Loading of Oxygen in the Lungs

Picture the loading of oxygen onto hemoglobin as blood passes through the alveolar-capillary system at a time when the alveolar oxygen tension PA_{O_2} is moderately low—say, 60 mm Hg (caused, for example, by an acute asthmatic episode). Normally, when the PA_{O_2} is 60 mm Hg, the P_{O_2} of the pulmonary capillary blood (P_{CO2}) is also about 60 mm Hg. Thus, the hemoglobin is about 90 percent saturated with oxygen as it leaves the alveoli (Figure 6–7). If, however, the oxyhemoglobin dissociation curve shifts to the right, as indicated in Figure 6–8 (caused by a pH of about 7.1), the hemoglobin will be only about 75 percent saturated with oxygen as it leaves the alveoli—despite the fact that the patient's plasma P_{O_2} is still 60 mm Hg.

In view of this gas transport phenomenon, therefore, it should be stressed that *the total oxygen delivery may be much lower than indicated by a particular Pa_{O_2} value when a disease process is present that causes*

FIGURE 6-7 Normally, when the PA_{O_2} is 60 mm Hg, the plasma P_{O_2} of the alveolar-capillary blood is also about 60 mm Hg and the hemoglobin is about 90 percent saturated with oxygen as it leaves the alveoli.

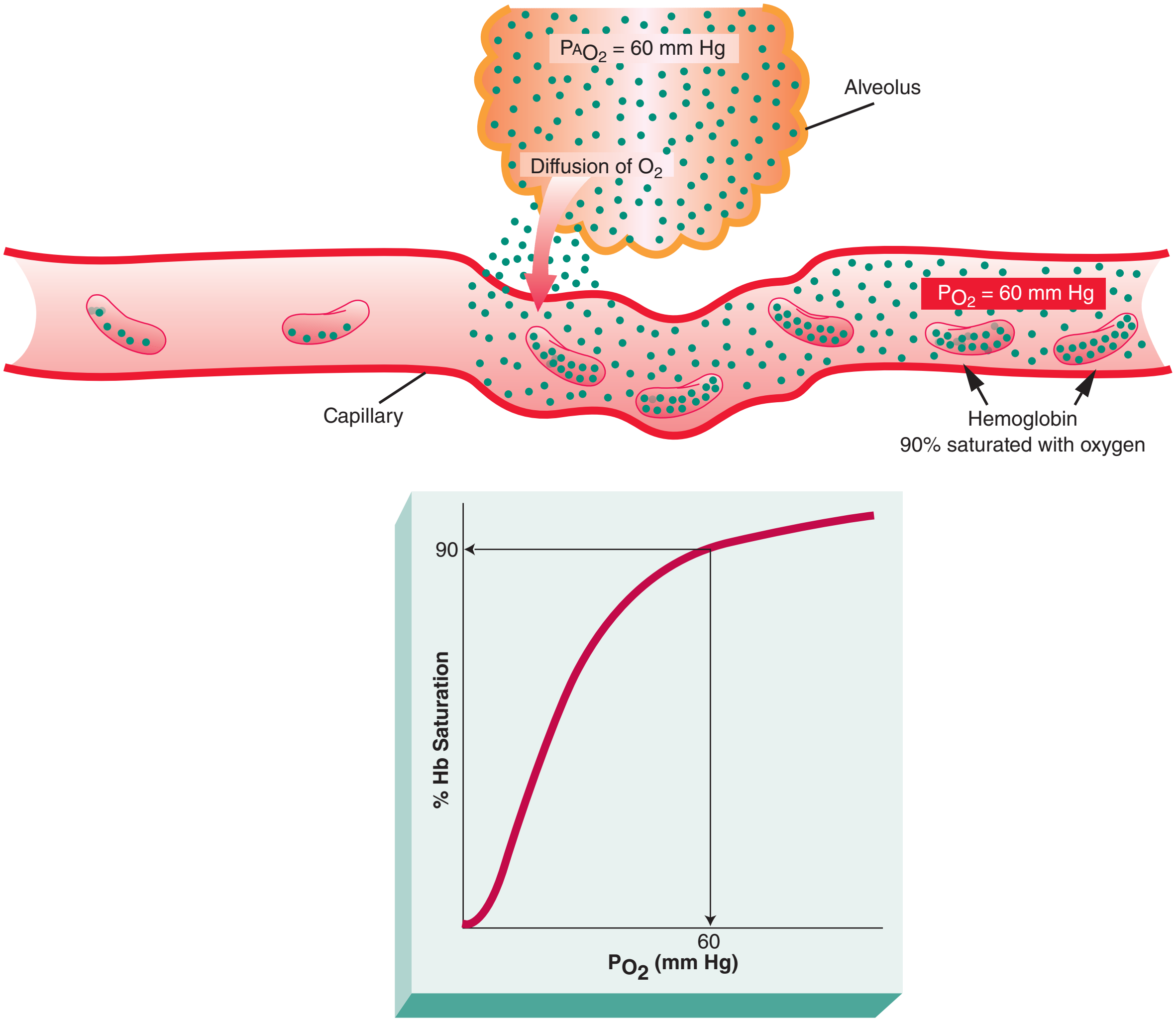
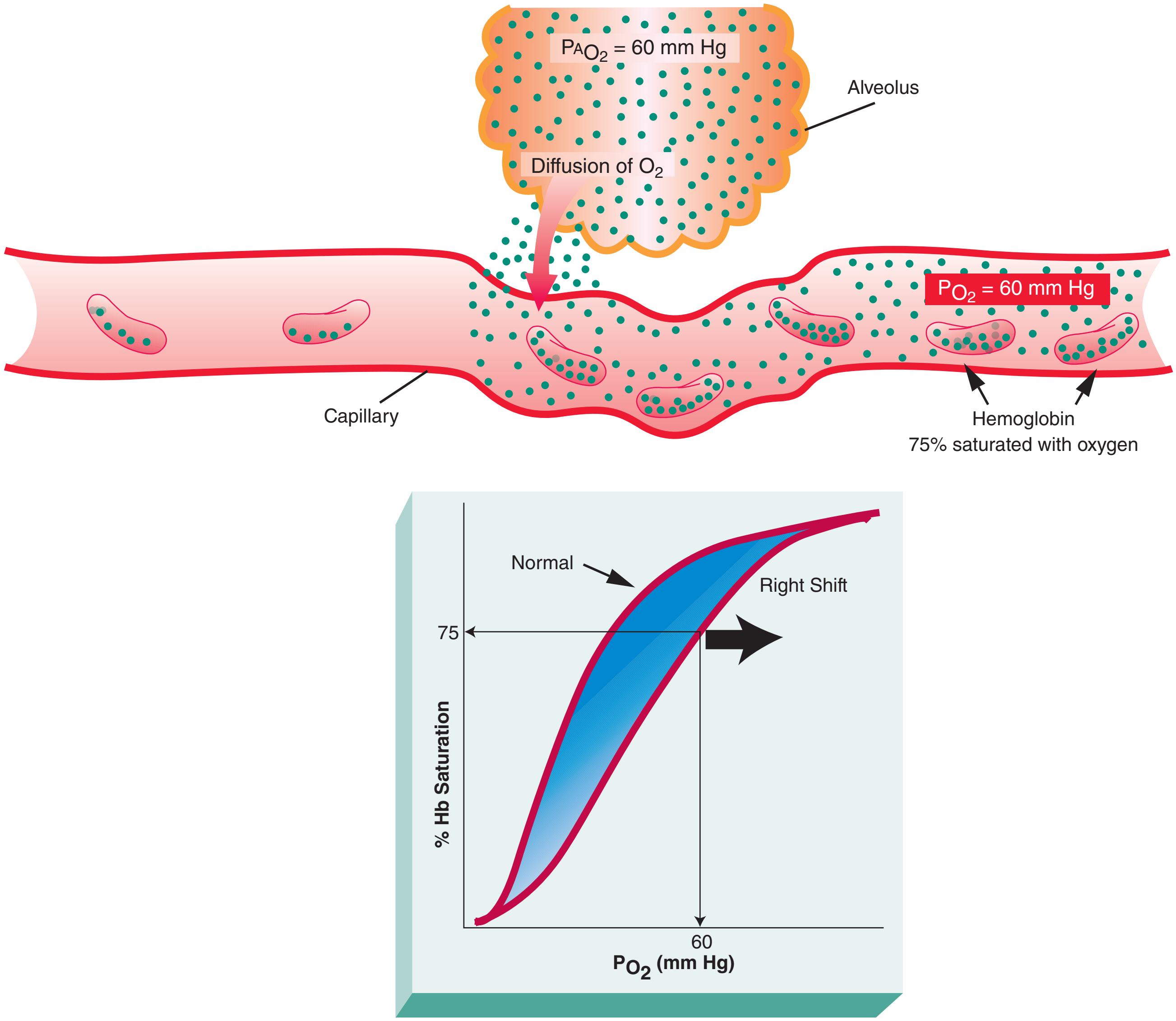


FIGURE 6-8 When the PA_{O_2} is 60 mm Hg at a time when the oxyhemoglobin dissociation curve has shifted to the right because of a pH of 7.1, the hemoglobin will be only about 75 percent saturated with oxygen as it leaves the alveoli.


PA_{O_2} = 60 mm Hg
Alveolus
Diffusion of O_2
P_{O_2} = 60 mm Hg
Capillary
Hemoglobin
75% saturated with oxygen
Normal
Right Shift
75
% Hb Saturation
60
P_{O_2} (mm Hg)

the oxyhemoglobin dissociation curve to shift to the right (see Figure 6–6). However, as discussed later, the unloading of oxygen at the tissue sites is actually enhanced when the oxyhemoglobin dissociation curve is shifted to the right. This action helps to offset the decreased loading of oxygen between the alveoli and pulmonary capillaries when the curve is shifted to the right. Note also that when a right shift is accompanied by either a decreased cardiac output or a reduced level of hemoglobin, the patient's ability to transport oxygen will be jeopardized even more.

Right Shifts—Unloading of Oxygen at the Tissues

Although the total oxygen delivery may decrease in the above situation, the plasma P_{O_2} at the tissue sites does not have to fall as much to unload oxygen from the hemoglobin. For example, if the tissue cells metabolize 5 mL/dL oxygen at a time when the oxyhemoglobin dissociation curve is in its normal position, the plasma P_{O_2} must fall from 60 mm Hg to about 35 mm Hg to free 5 mL/dL oxygen from the hemoglobin (Figure 6–9). If, however, the curve shifts to the right in response to a pH of 7.1, the plasma P_{O_2} at the tissue sites would only have to fall from 60 mm Hg to about 40 mm Hg to unload 5 mL/dL oxygen from the hemoglobin (Figure 6–10).

Left Shifts—Loading of Oxygen in the Lungs

If the oxyhemoglobin dissociation curve shifts to the left, as indicated in Figure 6–11 (caused by a pH of about 7.6), at a time when the $P_{A_{O_2}}$ is 60 mm Hg, the hemoglobin will be about 95 percent saturated with oxygen as it leaves the alveoli, even though the patient's plasma P_{O_2} is only 60 mm Hg.

FIGURE 6-9 Normally, when the plasma P_{O_2} is 60 mm Hg, the P_{O_2} must fall from 60 mm Hg to about 35 mm Hg to free 5 mL/dL oxygen from the hemoglobin for tissue metabolism.

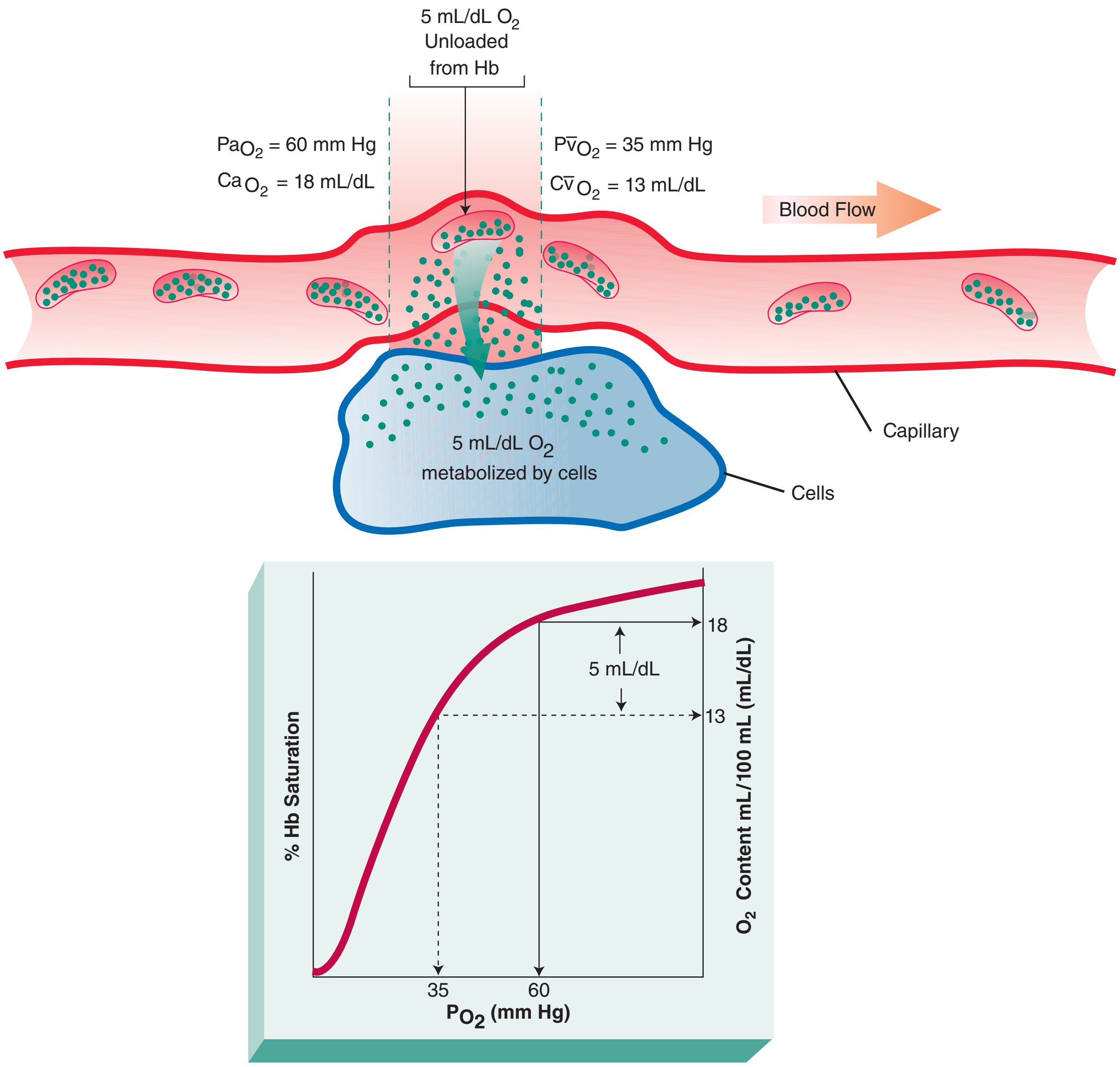
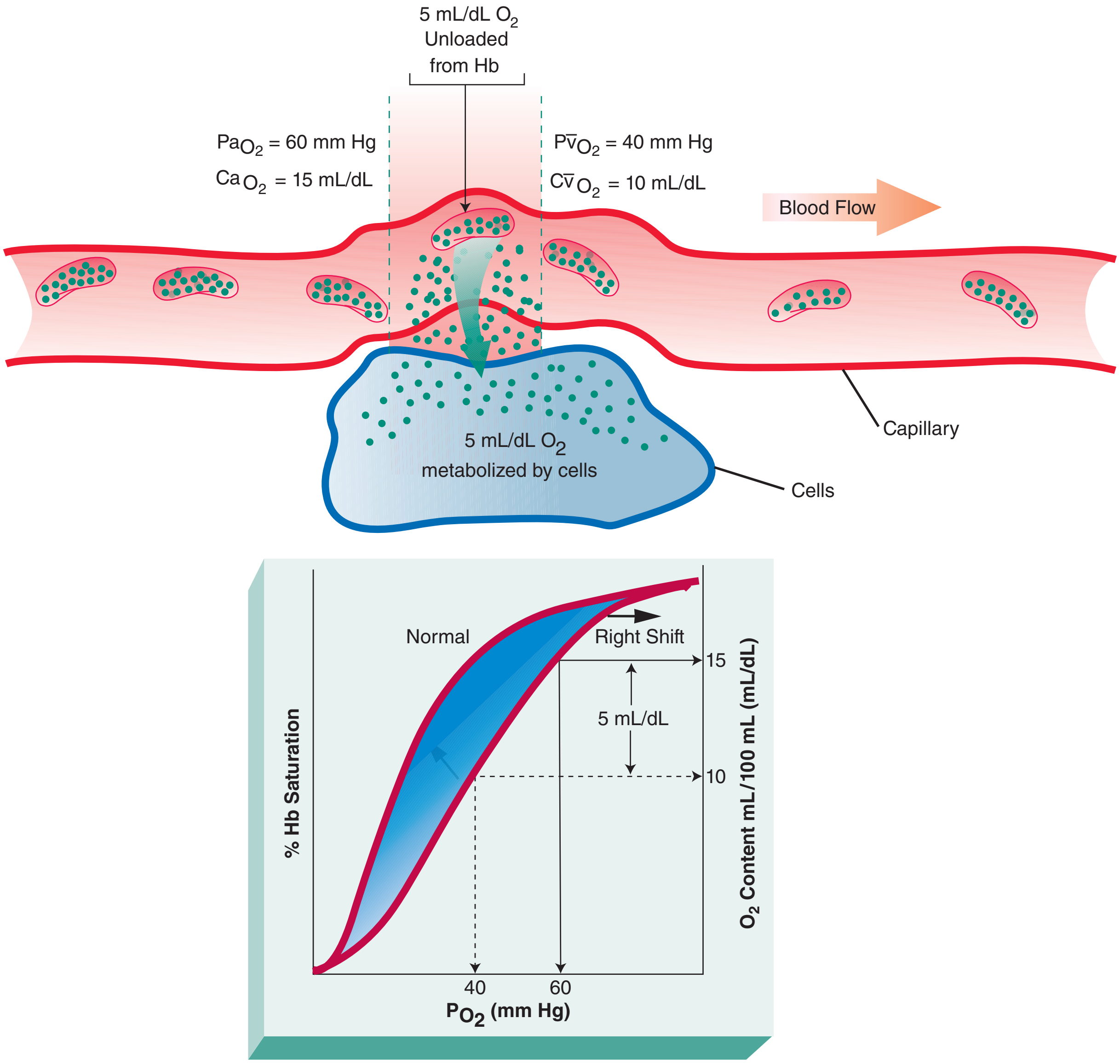

5 mL/dL O2 Unloaded from Hb
PaO2 = 60 mm Hg
CaO2 = 18 mL/dL
PV̄O2 = 35 mm Hg
CV̄O2 = 13 mL/dL
Blood Flow
Capillary
5 mL/dL O2 metabolized by cells
Cells
% Hb Saturation
O2 Content mL/100 mL (mL/dL)
18
5 mL/dL
13
35
60
PO2 (mm Hg)

FIGURE 6-10 When the Pa_{O_2} is 60 mm Hg at a time when the oxyhemoglobin dissociation curve has shifted to the right because of a pH of 7.1, the plasma P_{O_2} at the tissue site would have to fall from 60 mm Hg to about 40 mm Hg to unload 5 mL/dL oxygen from hemoglobin.


5 mL/dL O2 Unloaded from Hb
PaO2 = 60 mm Hg
CaO2 = 15 mL/dL
Pv̄O2 = 40 mm Hg
Cv̄O2 = 10 mL/dL
Blood Flow
Capillary
Cells
5 mL/dL O2 metabolized by cells
Normal
Right Shift
15
5 mL/dL
10
% Hb Saturation
O2 Content mL/100 mL (mL/dL)
40
60
PO2 (mm Hg)

Left Shifts—Unloading of Oxygen at the Tissues

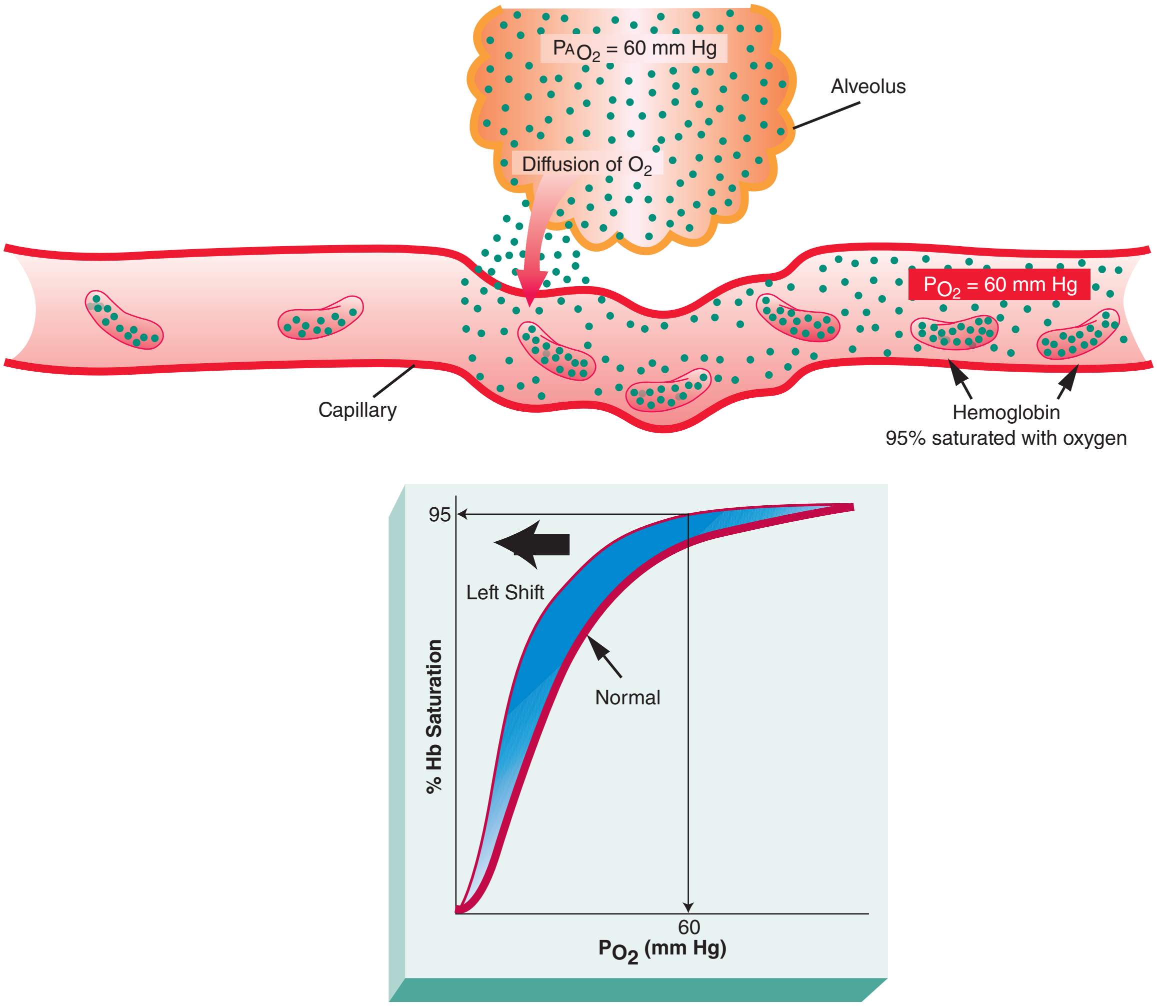
Although the total oxygen delivery increases in the previously mentioned situation, the plasma P_{O_2} at the tissue sites must decrease more than normal in order for oxygen to dissociate from the hemoglobin. For example, if the tissue cells require 5 mL/dL oxygen at a time when the oxyhemoglobin dissociation curve is normal, the plasma P_{O_2} will fall from 60 mm Hg to about 35 mm Hg to free 5 mL/dL of oxygen from the hemoglobin (see Figure 6–9). If, however, the curve shifts to the left because of a pH of 7.6, the plasma P_{O_2} at the tissue sites would have to fall from 60 mm Hg to about 30 mm Hg in order to unload 5 mL/dL oxygen from the hemoglobin (Figure 6–12).

Clinical Connection 6-4

Case Study—The Significance of a Right Shift in the Oxyhemoglobin Dissociation Curve

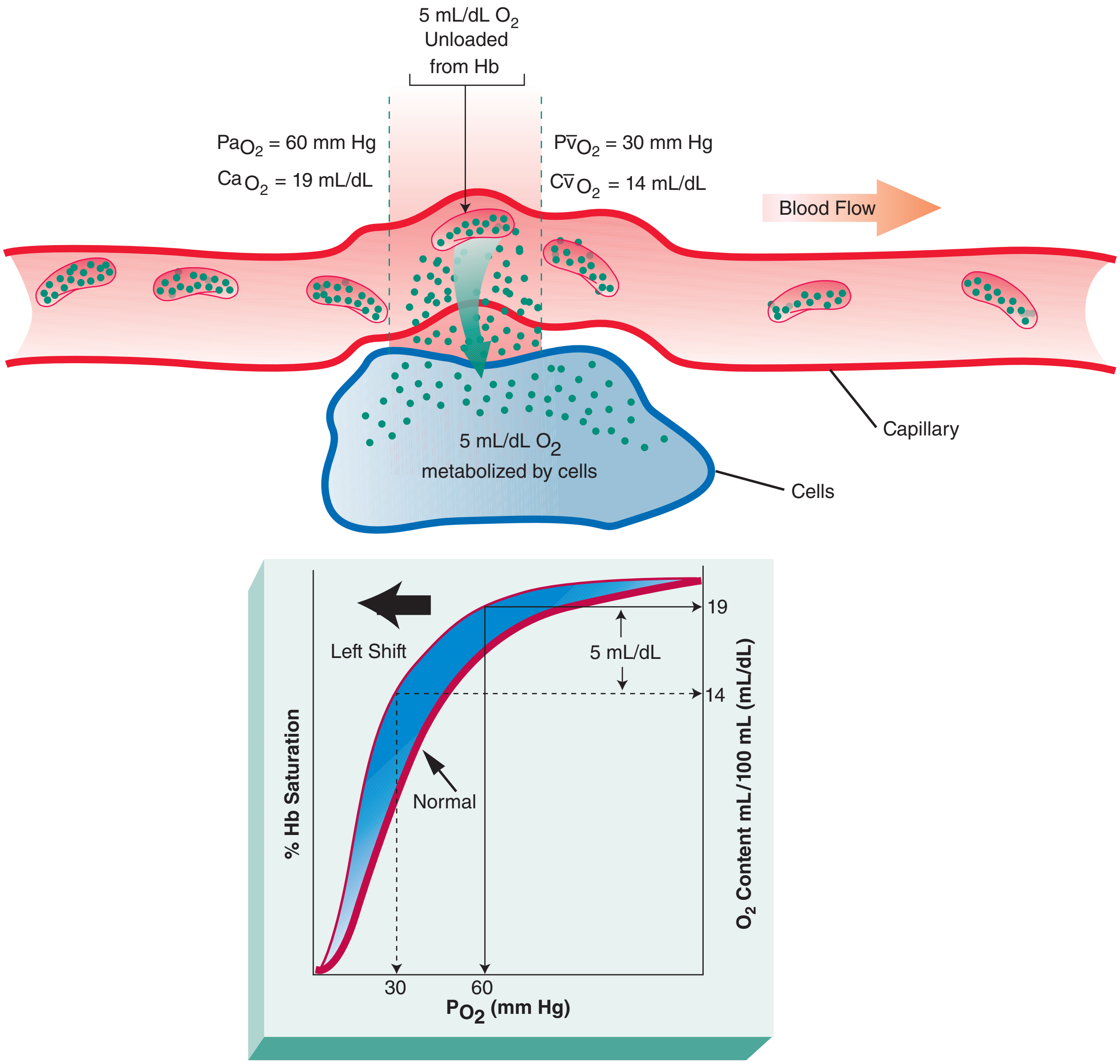
In the Clinical Application Case 2 (page 304), the respiratory therapist is called to assist in the care of an 18-year-old woman who presents in the emergency department in severe respiratory distress during an asthmatic episode. This case illustrates how a right shift in the oxygen dissociation—produced by a decreased pH and an increased Pa_{CO_2} level—causes (1) a decrease in the loading of oxygen as hemoglobin passes through the lungs and (2) a decrease in the patient's total oxygen delivery. This case effectively highlights that when additional clinical factors are present—that shift the oxygen dissociation curve to the right, or left—the respiratory therapist must take into account these factors in the final analysis of the patient's overall oxygenation status.

FIGURE 6-11 When the $P_{A_{O_2}}$ is 60 mm Hg at a time when the oxyhemoglobin dissociation curve has shifted to the left because of a pH of 7.6, the hemoglobin will be about 95 percent saturated with oxygen as it leaves the alveoli.



$P_{A_{O_2}}$ = 60 mm Hg
Alveolus
Diffusion of O_2
P_{O_2} = 60 mm Hg
Capillary
Hemoglobin
95% saturated with oxygen
95
Left Shift
Normal
% Hb Saturation
60
P_{O_2} (mm Hg)

FIGURE 6-12 When the Pa_{O_2} is 60 mm Hg at a time when the oxyhemoglobin dissociation curve has shifted to the left because of a pH of 7.6, the plasma P_{O_2} at the tissue sites would have to fall from 60 mm Hg to about 30 mm Hg to unload 5 mL/dL oxygen from the hemoglobin.


5 mL/dL O2
Unloaded
from Hb
PaO2 = 60 mm Hg
CaO2 = 19 mL/dL
Pv̄O2 = 30 mm Hg
Cv̄O2 = 14 mL/dL
Blood Flow
Capillary
5 mL/dL O2
metabolized by cells
Cells
Left Shift
5 mL/dL
19
14
Normal
% Hb Saturation
O2 Content mL/100 mL (mL/dL)
30
60
PO2 (mm Hg)

Oxygen Transport Calculations

Various mathematical manipulations of the Ca_{O_2},$C\bar{v}_{O_2}$ and Cc_{O_2} values can serve as excellent indicators of an individual's cardiac and ventilatory status. Clinically, the most common oxygen transport studies performed are (1) total oxygen delivery, (2) arterial-venous oxygen content difference, (3) oxygen consumption, (4) oxygen extraction ratio, (5) mixed venous oxygen saturation, and (6) pulmonary shunting.[8]

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[8] See Appendix V for a representative example of a cardiopulmonary profile sheet used to monitor the oxygen transport status of the critically ill patient.

Total Oxygen Delivery

The total amount of oxygen delivered or transported to the peripheral tissues is dependent on (1) the body's ability to oxygenate blood, (2) the hemoglobin concentration, and (3) the cardiac output ($\dot{Q}$). **Total oxygen delivery** (D_{O_2}) is calculated as follows:

$$D_{O_2} = \dot{Q}_T \times (Ca_{O_2} \times 10)$$

where $\dot{Q}_T$ is total cardiac output (L/min), Ca_{O_2} is the oxygen content of arterial blood (mL oxygen/100 mL blood), and the factor 10 is needed to convert the Ca_{O_2} to mL O_2/L blood.

For example, if an individual has a cardiac output of 5 L/min and a Ca_{O_2} of 20 mL/dL, the total amount of oxygen delivered to the peripheral tissues will be about 1000 mL of oxygen per minute:

$$\begin{aligned} D_{O_2} &= \dot{Q}_T \times (Ca_{O_2} \times 10) \\ &= 5\text{ L} \times (20\text{ mL/dL} \times 10) \\ &= 1000\text{ mL }O_2\text{/min} \end{aligned}$$

Oxygen delivery decreases when there is a decline in (1) blood oxygenation, (2) hemoglobin concentration, or (3) cardiac output. When possible, an individual's hemoglobin concentration or cardiac output will often increase in an effort to compensate for a reduced oxygen delivery.

Arterial-Venous Oxygen Content Difference

The **arterial-venous oxygen content difference**, $C(a - \bar{v})_{O_2}$, is the difference between the Ca_{O_2} and the $C\bar{v}_{O_2}$ ($Ca_{O_2} - C\bar{v}_{O_2}$). Clinically, the mixed venous blood needed to compute the $C\bar{v}_{O_2}$ is obtained from the patient's pulmonary artery.

Normally, the Ca_{O_2} is about 20 mL/dL and the $C\bar{v}_{O_2}$ is 15 mL/dL (Figure 6–13). Thus, the normal $C(a - \bar{v})_{O_2}$ is about 5 mL/dL:

$$\begin{aligned} C(a - \bar{v})_{O_2} &= Ca_{O_2} - C\bar{v}_{O_2} \\ &= 20\text{ mL/dL} - 15\text{ mL/dL} = 5\text{ mL/dL} \end{aligned}$$

In other words, 5 mL of oxygen are extracted from each 100 mL of blood for tissue metabolism (50 mL O_2/L). Because the average individual has a cardiac output of about 5 L/min and a $C(a - \bar{v})_{O_2}$ of about 5 mL/dL, approximately 250 mL of oxygen are extracted from the blood during the course of 1 minute (50 mL O_2/L × 5 L/min).

Clinically, the $C(a - \bar{v})_{O_2}$ can provide useful information regarding the patient's cardiopulmonary status because oxygen changes in mixed venous blood can occur earlier than oxygen changes in an arterial blood gas. Table 6–2 lists factors that can cause the $C(a - \bar{v})_{O_2}$ to increase. Factors that can cause the $C(a - \bar{v})_{O_2}$ to decrease are listed in Table 6–3.

Oxygen Consumption

The amount of oxygen extracted by the peripheral tissues during the period of 1 minute is called **oxygen consumption**, or *oxygen uptake* ($\dot{V}_{O_2}$). An individual's oxygen consumption is calculated by using this formula:

$$\dot{V}_{O_2} = \dot{Q}_T [C(a - \bar{v})_{O_2} \times 10]$$

where $\dot{Q}_T$ is the total cardiac output (L/min), $C(a - \bar{v})_{O_2}$ is the arterial-venous oxygen content difference ($Ca_{O_2} - C\bar{v}_{O_2}$), and the factor 10 is needed to convert the $C(a - \bar{v})_{O_2}$ to mL O_2/L.

FIGURE 6-13 Oxyhemoglobin dissociation curve. The normal oxygen content difference between arterial and venous blood is about 5 mL/dL. Note that both the right side and the left side of the graph illustrate that approximately 25 percent of the available oxygen is used for tissue metabolism and, therefore, the hemoglobin returning to the lungs is normally about 75 percent saturated with oxygen.

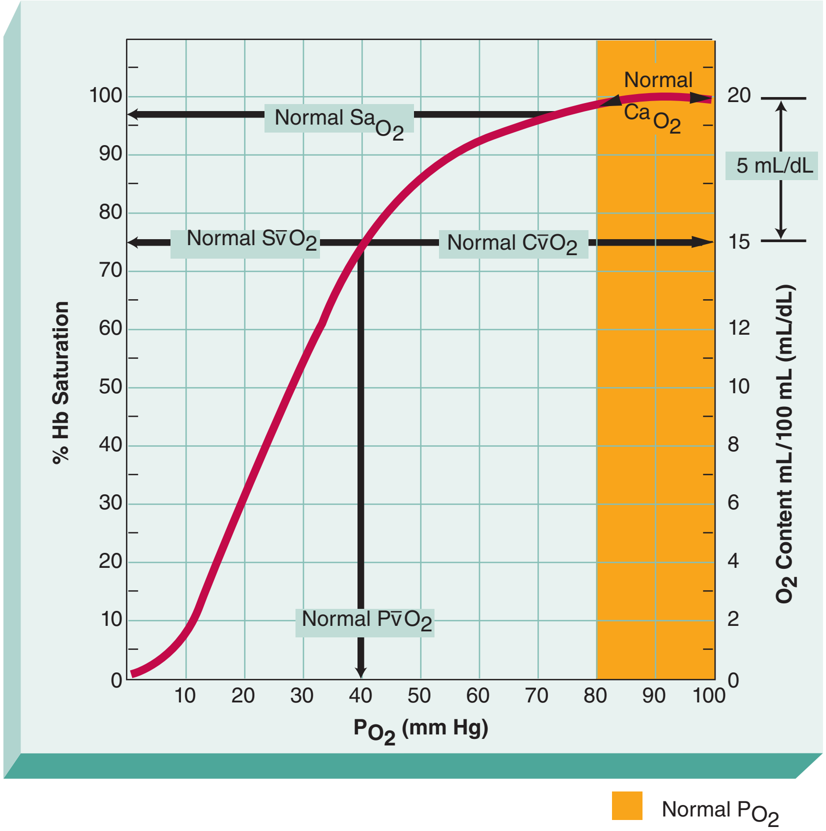

TABLE 6-2 **Factors That Increase the $C(a - \bar{v})_{O_2}$**

- Decreased cardiac output
- Periods of increased oxygen consumption
  - Exercise
  - Seizures
  - Shivering
  - Hyperthermia

TABLE 6-3 **Factors That Decrease the $C(a - \bar{v})_{O_2}$**

- Increased cardiac output
- Skeletal muscle relaxation (e.g., induced by drugs)
- Peripheral shunting (e.g., sepsis, trauma)
- Certain poisons (e.g., cyanide prevents cellular metabolism)
- Hypothermia

For example, if an individual has a cardiac output of 5 L/min and a $C(a - \bar{v})_{O_2}$ of 5 mL/dL, the total amount of oxygen metabolized by the tissues in 1 minute will be 250 mL:

$$\begin{aligned}\dot{V}_{O_2} &= \dot{Q}_T\,[C(a - \bar{v})_{O_2} \times 10] \\ &= 5 \text{ L/min} \times 5 \text{ mL/dL} \times 10 \\ &= 250 \text{ mL } O_2\text{/min}\end{aligned}$$

Clinically, the oxygen consumption is usually related to the patient's body surface area (BSA) (see Appendix IV), because the amount of oxygen extracted by the peripheral cells varies with an individual's height and weight. The patient's oxygen consumption index is derived by dividing the $\dot{V}_{O_2}$ by the BSA. The average oxygen consumption index ranges between 125 to 165 mL O_2/m^2.

Factors that cause an increase in oxygen consumption are listed in Table 6–4. Table 6–5 lists factors that cause a decrease in oxygen consumption.

TABLE 6-4

Factors That Increase the $\dot{V}_{O_2}$
Exercise
Seizures
Shivering
Hyperthermia

TABLE 6-5

Factors That Decrease the $\dot{V}_{O_2}$
Skeletal muscle relaxation (e.g., induced by drugs)
Peripheral shunting (e.g., sepsis, trauma)
Certain poisons (e.g., cyanide prevents cellular metabolism)
Hypothermia

Clinical Connection 6-5

Metabolic Demands—Variation among Animal Species[9]

It is important to understand that living organisms have systems in place to maintain homeostasis in a vast array of circumstances. Peak performance, exercise, and exertion can tax the cardiopulmonary system's capabilities to its maximum. Sleep, rest, and, for those species that do so, hibernation place lower demands on the cardiopulmonary system. Additionally, there is a large degree of variability across animal species. Each animal species has cardiopulmonary function suited to meet and match its physiologic demands.

When the metabolic demands increase, the cardiopulmonary system responds proportionately to meet the needs of the body cells—that is, to increase the delivery of oxygen and nutrients to the cells while also removing carbon dioxide and waste products equal to the rate of production. In cases where

(*Continued*)

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[9] Akhlesh Lakhtakia and Raul J. Martin-Palma (eds.), *Engineered Biomimicry* (Elsevier, 2013), pp. xix–xxii. Reference for pronghorn antelope. Websites:

- https://www.nps.gov/romo/learn/nature/marmot.htm.
- https://www.researchgate.net/publication/6757434_Hypoxia_Tolerance_in_Mammals_and_Birds_From_the_Wilderness_to_the_Clinic.

Clinical Connection 6-5, Continued

metabolism is slowed, an extreme case being animal hibernation, the demands to the cardiopulmonary system are less taxed and the respiratory rate, heart rate, and cardiac output are decreased proportionately to the decrease in metabolic demand.

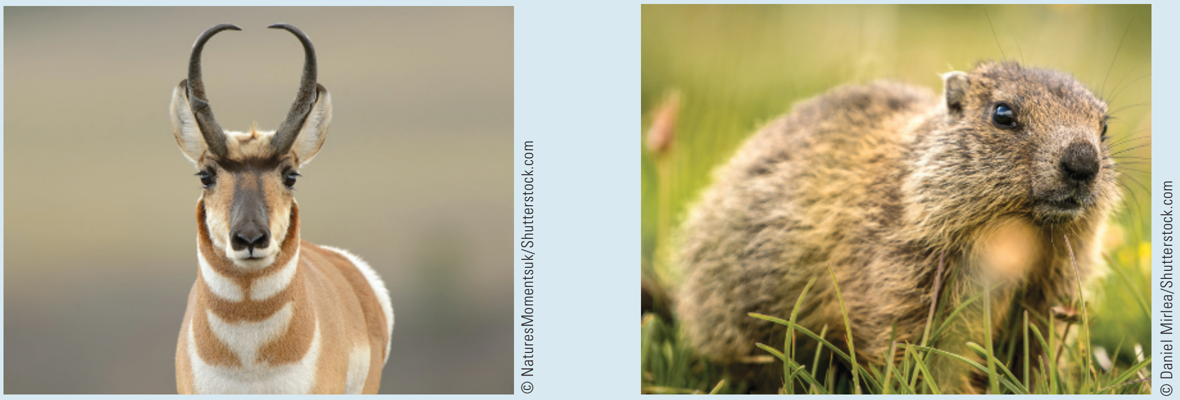
Not only does oxygen consumption vary among humans—from normal individuals to elite athletes—oxygen consumption is also highly variable among animal species. While resting oxygen consumption for a human is approximately 3.5 mL/Kg, well-trained runners may have oxygen consumption rates in the 60-mL/Kg range during peak performance. The **pronghorn antelope** is purported to have an oxygen consumption rate of about 300 mL/Kg (Figure 6–14). What impact does this have on the cardiopulmonary system's ability to meet and deliver this increased oxygen demand to the working cells? Although the pronghorn antelope weighs roughly the same as an adult human, it has a cardiac output that is about three times higher than a human. It also has proportionately larger lungs and a heart to meet the increased demands for gas exchange and pumping capabilities.

While exercise can tax the cardiopulmonary system to its maximum capabilities, consider the effects of hibernation and the subsequent decrease in metabolic activity. Van't Hoff's rule explains the benefit of hibernation: For every 10°C drop in body temperature, the metabolism slows by about half. This drop in metabolism decreases the demands placed on the cardiopulmonary system to supply oxygen and nutrients, and remove carbon dioxide and waste products. The marmot decreases its heart rate from an average of 160 beats/min to about 9 beats/min and decreases its respiratory rate to about 1–3 breaths per minute during hibernation (see Figure 6–14). During hibernation, the marmot's body temperature may fall from its normal temperature of about 37°C to as low as 5°C (41°F).

During hibernation, the demands on the cardiopulmonary system decrease to match the decrease in energy expenditure, oxygen consumption, and carbon dioxide production. The reduced metabolism and cardiopulmonary needs, in turn, eliminate the need for the marmot to eat during the entire hibernation period. The marmot adequately survives on its energy reserves stored in its body fat.

In conclusion, as metabolic demands increase or decrease, the cardiopulmonary system responds proportionately to meet the needs of the cells—that is to match the delivery of oxygen and nutrients to the cells while also removing carbon dioxide and waste products equal to the rate of production. When needed during peak performance or exertion, the cardiopulmonary system is called upon to increase the delivery of blood flow to meet the increased metabolic needs. In cases where metabolism is slowed, an extreme case being animal hibernation, the demands to the cardiopulmonary system are less taxed, and respiratory rate, heart rate, and cardiac output are decreased proportionately to the decrease in demand. The dynamic status of the cardiopulmonary status to change in response to changing metabolic demands shows the remarkable capability of organisms to maintain homeostasis in response to a variety of demands and stressors.

FIGURE 6-14 Pronghorn antelope and marmot.



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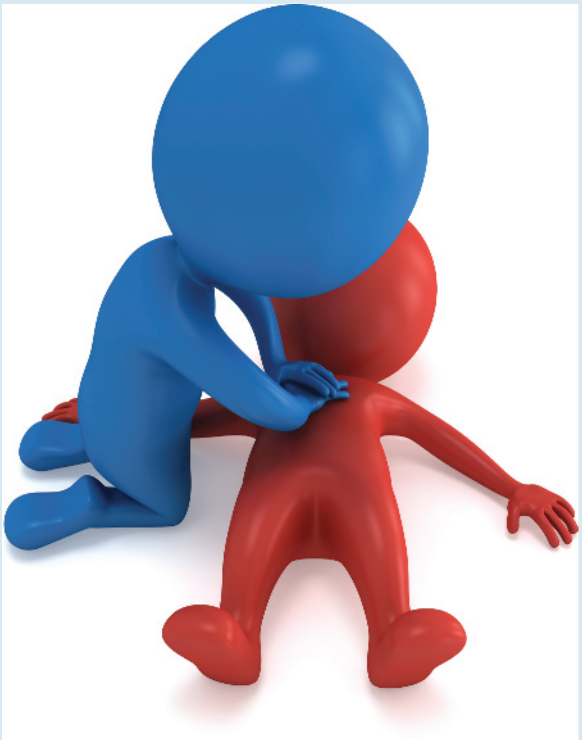
Clinical Connection 6-6

Cardiopulmonary Resuscitation (CPR)—Start as Early as Possible!

In sudden cardiac arrest, permanent brain damage can begin in as little as 4 minutes—and death can follow minutes later. When reflecting on the oxygen transport calculations—especially the **total oxygen delivery (D_{O_2})** and the **oxygen consumption ($\dot{V}_{O_2}$)** equations—the respiratory therapist can quickly develop a whole new appreciation for the basic cardiopulmonary physiology that supports the importance of starting CPR as early as possible—*ideally, within the first 4 minutes* (Figure 6-15)!

For example, let's first consider the relationship between the D_{O_2} equation and the $\dot{V}_{O_2}$ equation under normal, healthy conditions: The D_{O_2} calculation—the O_2 supply system equation—illustrates that about 1000 mL of oxygen are transported to the tissue cells each minute. On the other hand, the $\dot{V}_{O_2}$ calculation—the O_2 demand system equation—illustrates that of this 1000 mL, about 250 mL of oxygen are consumed by the tissue cells in the course of the metabolic process. Using the normal D_{O_2} and $\dot{V}_{O_2}$ relationship, let's consider the following basic math, time sequence, and oxygen consumption that typically occurs during a 4-minute period:

FIGURE 6-15 Cardiopulmonary resuscitation (CPR).



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Normal Oxygen Consumption over a 4-Minute Period

Time	Oxygen Metabolism by Tissue Cells
Minute 1	As the $\dot{V}_{O_2}$ calculation illustrates, the body normally consumes about ***250 mL* of O_2** each minute.
Minute 2	During the 2nd minute, the body continues to consume another 250 mL of O_2—for a **total *500 mL* O_2**.
Minute 3	During the 3rd minute, the body continues to consume another 250 mL O_2—for a **total of *750 mL* O_2**.
Minute 4	During the 4th minute, the body continues to consume another 250 mL of O_2—for a **total of *1000 mL* O_2**.

Thus, in just 4 minutes—under normal healthy conditions—the body consumes about 1000 mL O_2—a liter of oxygen.

Now let's consider what happens to the oxygen transport system during a sudden cardiac arrest: Immediately, the patient's entire blood flow throughout the body stops—and the blood pressure rapidly falls. In other words, the patient's entire blood volume—an average of about 5 L—becomes motionless when the heart stops beating. It is estimated that *only* about 5 percent of an individual's total blood volume is contained in the systemic capillary system at any given moment—that is, in the tissue oxygen utilization area. (Approximately 65 percent of the total blood volume is contained in the systemic veins and venules, about 15 percent is contained in the systemic arteries and arterioles, and about 15 percent is contained in the heart and pulmonary vessels.)

(*Continued*)

Clinical Connection 6-6, Continued

The bottom line is this: When the heart stops beating, only a small amount of the total blood volume—about 5 percent—is in the systemic capillary system. Only the oxygen contained in the systemic capillary blood is available for tissue metabolism. Once this oxygen is consumed, anaerobic metabolism, tissue cell damage, and death will quickly ensue.

Although it is impossible to determine the precise amount of oxygen in the systemic capillary system at any given moment and the rate at which the oxygen is being metabolized immediately after a cardiac arrest, it is known that a number of unfavorable mechanisms rapidly develop that adversely affect the patient's oxygenation status—including the following:

- The immediate stoppage of the oxygen delivery system—which, in turn, leads to anaerobic metabolism and lactic acidosis.
- The sudden stoppage of transporting the tissue CO_2 to the lungs for elimination—which, in turn, lead to a rapid accumulation of CO_2 throughout the body.
- The abrupt drop in pH—which is caused by the CO_2 accumulation and lactic acid accumulation.

Additional confounding factors may include (1) the patient's initial baseline oxygenation level, which may be low; (2) the patient's general health, which may be poor; and (3) the patient's age.

Thus, as one can easily see, the initiation of CPR as soon as possible in the cardiac arrest patient is absolutely critical! The tissue cells will continue to consume any available oxygen in the stagnated blood as long as possible. When it comes to CPR—and the administration of 100 percent oxygen—the earlier the better! The accompanying table provides an overview of the generally accepted likelihood of brain damage or death after a cardiac arrest.

Brain Damage after Cardiac Arrest

Time after Cardiac Arrest	Chances of Brain Damage
0–4 minutes	Minimal
4–6 minutes	Possible
6–10 minutes	Likely
>10 minutes	Brain death likely

Oxygen Extraction Ratio

The **oxygen extraction ratio** (O_2ER) is the amount of oxygen extracted by the peripheral tissues divided by the amount of oxygen delivered to the peripheral cells. The O_2ER is also known as the *oxygen coefficient ratio* or the *oxygen utilization ratio.*

The O_2ER is easily calculated by dividing the $C(a - \bar{v})_{O_2}$ by the Ca_{O_2}. In considering the normal Ca_{O_2} of 20 mL/dL, and the normal $C\bar{v}_O$ of 15 mL/dL (see Figure 6–13), the O_2ER ratio of the healthy individual is about 25 percent:

$$\begin{aligned} O_2ER &= \frac{Ca_{O_2} - C\bar{v}_{O_2}}{Ca_{O_2}} \\ &= \frac{20\text{ mL/dL} - 15\text{ mL/dL}}{20\text{ mL/dL}} \\ &= \frac{5\text{ mL/dL}}{20\text{ mL/dL}} \\ &= 0.25 \end{aligned}$$

Under normal circumstances, therefore, an individual's hemoglobin returns to the alveoli approximately 75 percent saturated with oxygen (see Figure 6-13). In an individual with a total oxygen delivery of

TABLE 6-6 Factors That Increase the O_2ER

- Decreased cardiac output
- Periods of increased oxygen consumption
  - Exercise
  - Seizures
  - Shivering
  - Hyperthermia
- Anemia
- Decreased arterial oxygenation

TABLE 6-7 Factors That Decrease the O_2ER

- Increased cardiac output
- Skeletal muscle relaxation (e.g., induced by drugs)
- Peripheral shunting (e.g., sepsis, trauma)
- Certain poisons (e.g., cyanide prevents cellular metabolism)
- Hypothermia (slows cellular metabolism)
- Increased hemoglobin concentration
- Increased arterial oxygenation

1000 mL/min, an extraction ratio of 25 percent would mean that during the course of 1 minute, 250 mL of oxygen are metabolized by the tissues and 750 mL of oxygen are returned to the lungs.

Factors that cause the O_2ER to increase are listed in Table 6–6. Table 6–7 lists factors that cause the O_2ER to decrease.

The O_2ER provides an important view of an individual's oxygen transport status that is not readily available from other oxygen transport measurements. For example, in an individual with normal Ca_{O_2} and normal $C\bar{v}_{O_2}$:

$$\begin{array}{rr} Ca_{O_2}: & 20\ \text{mL/dL} \\ -\,C\bar{v}_{O_2}: & 15\ \text{mL/dL} \\ \hline C(a-\bar{v})_{O_2} = & 5\ \text{mL/dL} \end{array}$$

the $C(a-\bar{v})_{O_2}$ is 5 mL/dL and the O_2ER is 25 percent (normal). However, in an individual with reduced Ca_{O_2} and reduced $C\bar{v}_{O_2}$:

$$\begin{array}{rr} Ca_{O_2}: & 10\ \text{mL/dL} \\ -\,C\bar{v}_{O_2}: & 5\ \text{mL/dL} \\ \hline C(a-\bar{v})_{O_2} = & 5\ \text{mL/dL} \end{array}$$

the $C(a-\bar{v})_{O_2}$ is still 5 mL/dL (assuming O_2 consumption remains constant), but the extraction ratio (O_2ER) is now 50 percent—clinically, a potentially dangerous situation.

Mixed Venous Oxygen Saturation

In the presence of a normal arterial oxygen saturation level Sa_{O_2} and hemoglobin concentration, the continuous monitoring of mixed venous oxygen saturation ($S\bar{v}_{O_2}$) is often used in the clinical setting to detect changes in the patient's $C(a-\bar{v})_{O_2}$, $\dot{V}_{O_2}$, and O_2ER. Normally, the ($S\bar{v}_{O_2}$) is about 75 percent (see Figure 6–13). Clinically, an ($S\bar{v}_{O_2}$) of about 65 percent is acceptable.

TABLE 6-8 Factors That Decrease the $S\bar{v}_{O_2}$\*

- Decreased cardiac output
- Periods of increased oxygen consumption
  - Exercise
  - Seizures
  - Shivering
  - Hyperthermia

*A decreased $S\bar{v}_{O_2}$ indicates that the $C(a - \bar{v})_{O_2}$, $\dot{V}_{O_2}$, and O_2ER are increasing.

TABLE 6-9 Factors That Increase the $S\bar{v}_{O_2}$\*

- Increased cardiac output
- Skeletal muscle relaxation (e.g., induced by drugs)
- Peripheral shunting (e.g., sepsis, trauma)
- Certain poisons (e.g., cyanide prevents cellular metabolism)
- Hypothermia

*An increased $S\bar{v}_{O_2}$ indicates that the $C(a - \bar{v})_{O_2}$, $\dot{V}_{O_2}$, and O_2ER are decreasing.

Factors that can cause the $S\bar{v}_{O_2}$ to decrease are listed in Table 6–8. Table 6–9 lists factors that can cause the $S\bar{v}_{O_2}$ to increase.

Continuous $S\bar{v}_{O_2}$ monitoring can signal changes in the patient's $C(a - \bar{v})_{O_2}$, $\dot{V}_{O_2}$, and O_2ER earlier than routine arterial blood gas monitoring because the Pa_{O_2} and Sa_{O_2} levels are often normal during early $C(a - \bar{v})_{O_2}$, $\dot{V}_{O_2}$, and O_2ER changes. Table 6–10 summarizes how various clinical factors may alter an individual's D_{O_2}, $\dot{V}_{O_2}$, $C(a - \bar{v})_{O_2}$, O_2ER, and $S\bar{v}_{O_2}$.

Pulmonary Shunting

Pulmonary shunting is defined as that portion of the cardiac output that moves from the right side to the left side of the heart without being exposed to alveolar oxygen (PA_{O_2}). Clinically, pulmonary shunting can be subdivided into (1) *absolute shunts* (also called *true shunt*) and (2) *relative shunts* (also called *shunt-like effects*).

Absolute Shunt

Absolute shunts (also called *true shunts*) can be grouped under two major categories: *anatomic shunts* and *capillary shunts*.

Anatomic Shunts. An **anatomic shunt** exists when blood flows from the right side of the heart to the left side without coming in contact with an alveolus for gas exchange (see Figure 16B). In the healthy lung, there is a normal anatomic shunt of about 3 percent of the cardiac output. This normal shunting is caused by nonoxygenated blood completely bypassing the alveoli and entering (1) the pulmonary vascular system by means of the bronchial venous drainage and (2) the left atrium by way of the thebesian veins. The following are common abnormalities that cause anatomic shunting:

- **Congenital heart disease.** Certain congenital defects permit blood to flow directly from the right side of the heart to the left side without going through the alveolar capillary system for gas exchange. Congenital heart defects include ventricular septum defect or newborns with persistent fetal circulation.

TABLE 6-10 Clinical Factors Affecting Various Oxygen Transport Calculation Values

	Oxygen Transport Calculations				
Clinical Factors	D_{O_2} (1000 mL O_2/min)	$\dot{V}_{O_2}$ (250 mL O_2/min)	$C(a - \bar{v})_{O_2}$ (5 mL/dL)	O_2ER (25%)	$S\bar{v}_{O_2}$ (75%)
↑ O_2 Loading in the lungs ↑ Hb ↑ Pa_{O_2} ↓ Pa_{CO_2} ↑ pH ↓ Temperature	↑	Same	Same	↓	↑
↓ O_2 Loading in the lungs ↓ Hb ↑ Pa_{CO_2} ↓ pH ↓ Pa_{O_2} Anemia ↑ Temperature	↓	Same	Same	↑	↓
↑ Metabolism Exercise Seizures Hyperthermia Shivering	Same	↑	↑	↑	↓
↓ Metabolism Hypothermia Skeletal muscle relaxation (e.g., drug induced)	Same	↓	↓	↓	↑
↓ Cardiac output	↓	Same	↑	↑	↓
↑ Cardiac output	↑	Same	↓	↓	↑
Peripheral shunting (e.g., sepsis, trauma)	Same	↓	↓	↓	↑
Certain poisons (e.g., cyanide)	Same	↓	↓	↓	↑

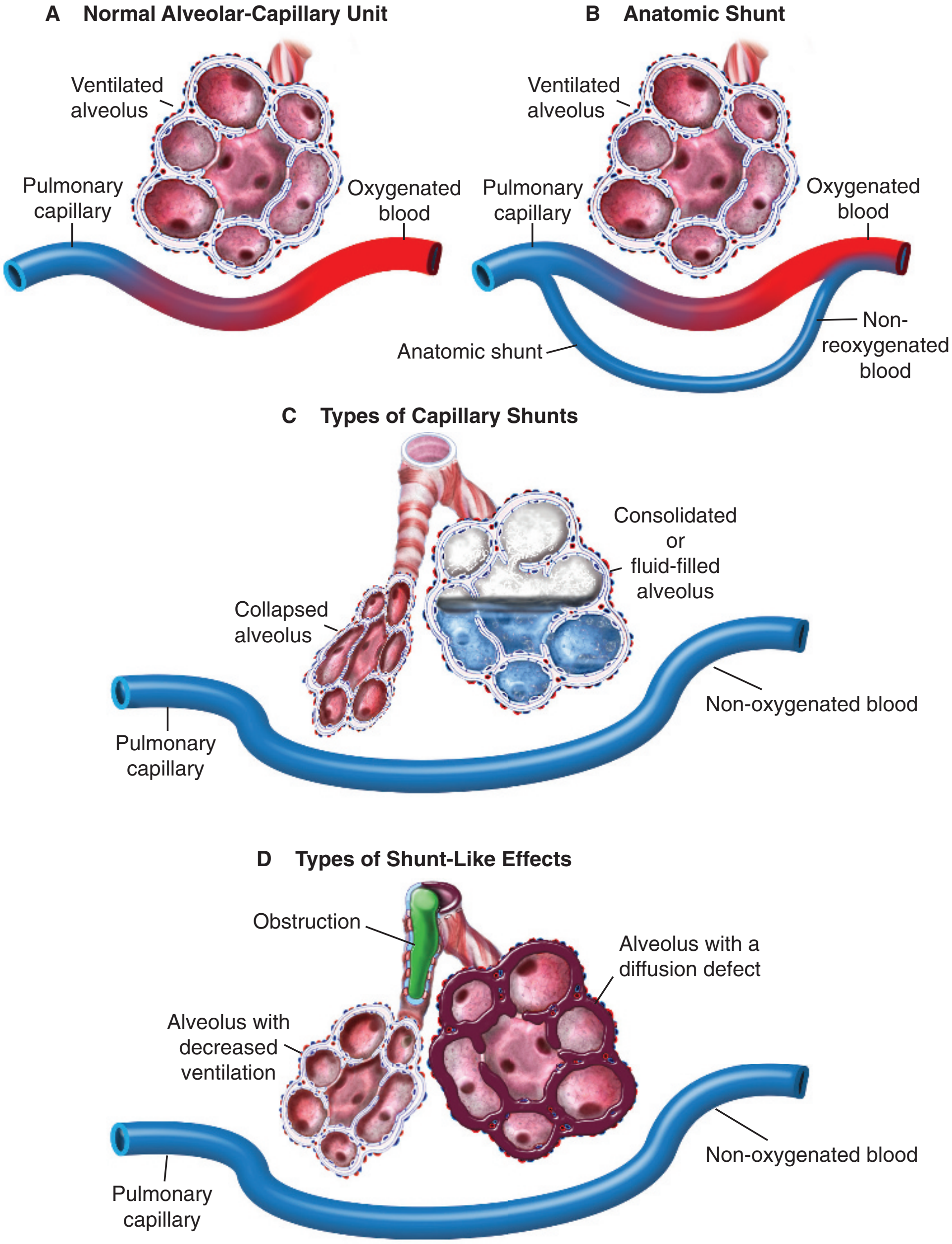
↑ = increased; ↓ = decreased.

- **Intrapulmonary fistula.** In this type of anatomic shunting, a right-to-left flow of pulmonary blood does not pass through the alveolar-capillary system. It may be caused by chest trauma or disease. For example, a penetrating chest wound that damages both the arteries and veins of the lung can leave an arterial-venous shunt as a result of the healing process.
- **Vascular lung tumors.** Some lung tumors can become very vascular. Some permit pulmonary arterial blood to move through the tumor mass and into the pulmonary veins without passing through the alveolar-capillary system.

Capillary Shunts. A **capillary shunt** is commonly caused by (1) alveolar collapse or atelectasis, (2) alveolar fluid accumulation, or (3) alveolar consolidation (Figure 6–16C).

The sum of the anatomic shunt and capillary shunt is referred to as the *absolute,* or *true, shunt*. Clinically, patients with absolute shunting respond poorly to oxygen therapy because alveolar oxygen does not come in contact with the shunted blood. Absolute shunting is *refractory* to oxygen therapy; that is, the reduced arterial oxygen level produced by this form of pulmonary shunting cannot be treated simply by increasing the concentration of inspired oxygen because (1) the alveoli are unable to accommodate any form of ventilation, and (2) the blood that bypasses functional alveoli cannot carry more oxygen once it has become fully saturated—except for a very small amount that dissolves in the plasma ($P_{O_2} \times 0.003 =$ dissolved O_2).

FIGURE 6-16 Pulmonary shunting: **(A)** normal alveolar-capillary unit; **(B)** anatomic shunt; **(C)** types of capillary shunts; **(D)** types of shunt-like effects.


A Normal Alveolar-Capillary Unit
Ventilated alveolus
Pulmonary capillary
Oxygenated blood
B Anatomic Shunt
Ventilated alveolus
Pulmonary capillary
Oxygenated blood
Anatomic shunt
Non-reoxygenated blood
C Types of Capillary Shunts
Consolidated or fluid-filled alveolus
Collapsed alveolus
Pulmonary capillary
Non-oxygenated blood
D Types of Shunt-Like Effects
Obstruction
Alveolus with a diffusion defect
Alveolus with decreased ventilation
Pulmonary capillary
Non-oxygenated blood

Relative Shunt

When pulmonary capillary perfusion is in excess of alveolar ventilation, a **relative shunt**, or **shunt-like effect**, is said to exist (Figure 6–16D). Common causes of this form of shunting include (1) hypoventilation, (2) ventilation/perfusion mismatches (e.g., chronic emphysema, bronchitis, asthma, and excessive airway secretions), and (3) alveolar-capillary diffusion defects (e.g., alveolar fibrosis or alveolar edema).

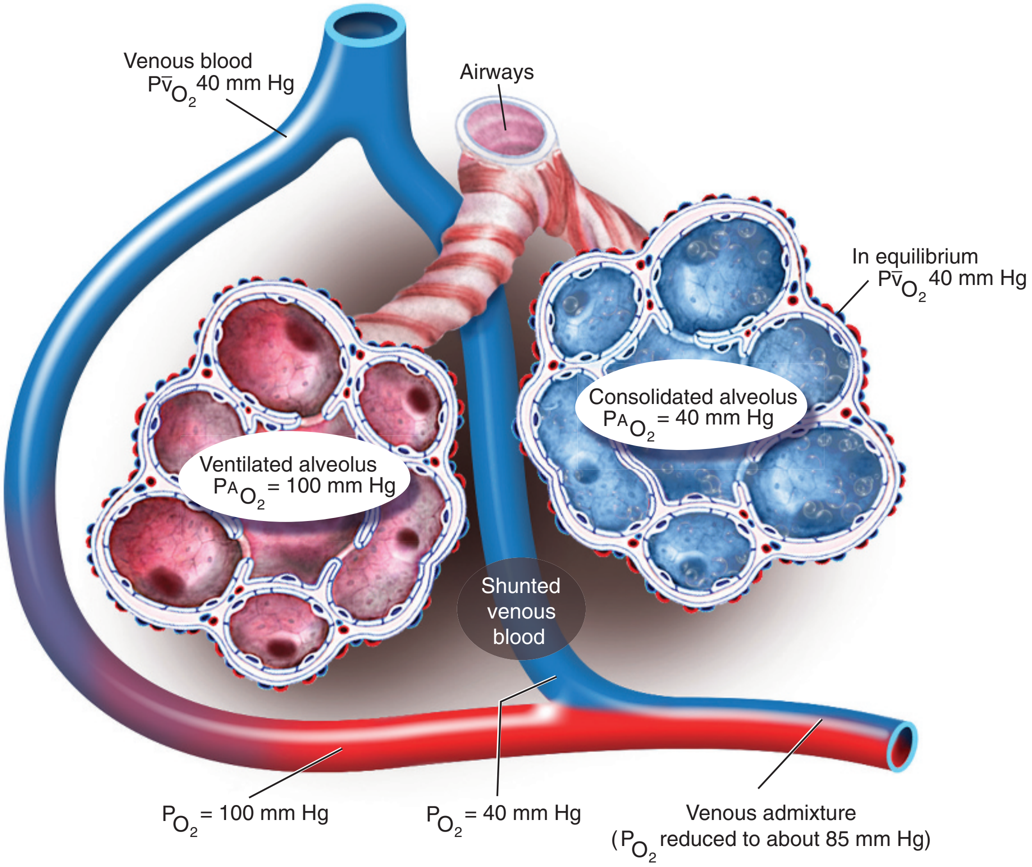
Even though the alveolus may be ventilated in the presence of an alveolar-capillary defect, the blood passing by the alveolus does not have enough time to equilibrate with the alveolar oxygen tension. If the diffusion defect is severe enough to completely block gas exchange across the alveolar-capillary membrane, the shunt is referred to as an *absolute* or *true shunt* (see preceding section). Relative shunting may also occur following the administration of drugs that cause an increase in cardiac output or dilation of the pulmonary vessels. Conditions that cause a shunt-like effect are readily corrected by oxygen therapy. In other words, they are not refractory to oxygen therapy.

Venous Admixture

The end result of pulmonary shunting is **venous admixture**. Venous admixture is the mixing of shunted, *non-oxygenated blood* with *reoxygenated blood* distal to the alveoli (i.e., downstream in the pulmonary venous system) (Figure 6-17). When venous admixture occurs, the shunted, non-reoxygenated blood gains oxygen molecules while, at the same time, the reoxygenated blood loses oxygen molecules.

This process continues until (1) the P_{O_2} throughout all of the plasma of the newly mixed blood is in equilibrium, and (2) all of the hemoglobin molecules carry the same number of oxygen molecules. The end result is a blood mixture that has a higher P_{O_2} and oxygen content than the original shunted, non-reoxygenated blood, but a lower P_{O_2} and oxygen content than the original reoxygenated blood. The final outcome of venous admixture is a reduced P_{O_2} and Ca_{O_2} returning to the left side of the heart. Clinically, it is this oxygen mixture that is evaluated downstream (e.g., from the radial artery) to determine an individual's arterial blood gases (see Table 6–1).

FIGURE 6-17 Venous admixture occurs when reoxygenated blood mixes with non-reoxygenated blood distal to the alveoli.


Venous blood
$P\bar{v}_{O_2}$ 40 mm Hg
Airways
In equilibrium
$P\bar{v}_{O_2}$ 40 mm Hg
Consolidated alveolus
$P_{A_{O_2}}$ = 40 mm Hg
Ventilated alveolus
$P_{A_{O_2}}$ = 100 mm Hg
Shunted venous blood
P_{O_2} = 100 mm Hg
P_{O_2} = 40 mm Hg
Venous admixture
(P_{O_2} reduced to about 85 mm Hg)

Shunt Equation

Because pulmonary shunting and venous admixture are common complications in respiratory disorders, knowledge of the degree of shunting is often desirable when developing patient care plans. The amount of intrapulmonary shunting can be calculated by using the **classic shunt equation**, which is written as follows:

$$\frac{\dot{Q}_S}{\dot{Q}_T} = \frac{Cc_{O_2} - Ca_{O_2}}{Cc_{O_2} - C\bar{v}_{O_2}}$$

where $\dot{Q}_S$ is cardiac output that is shunted, $\dot{Q}_T$ is total cardiac output, Cc_{O_2} is oxygen content of capillary blood, Ca_{O_2} is oxygen content of arterial blood, and $C\bar{v}_{O_2}$ is oxygen content of mixed venous blood.

To obtain the data necessary to calculate the degree of pulmonary shunting, the following clinical information must be gathered:

- P_B (barometric pressure)
- Pa_{O_2} (partial pressure of arterial oxygen)
- Pa_{CO_2} (partial pressure of arterial carbon dioxide)
- $P\bar{v}_{O_2}$ (partial pressure of mixed venous oxygen)
- Hb (hemoglobin concentration)
- $P_{A_{O_2}}$ (partial pressure of alveolar oxygen)
- $F_{I_{O_2}}$ (fractional concentration of inspired oxygen)

Case Study: Motorcycle Crash Victim

A 38-year-old man is on a volume-cycled mechanical ventilator on a day when the barometric pressure is 750 mm Hg. The patient is receiving an $F_{I_{O_2}}$ of 0.70. The following clinical data are obtained:

Hb: 13 g/dL
Pa_{O_2}: 50 mm Hg (Sa_{O_2} = 85%)
Pa_{CO_2}: 43 mm Hg
$P\bar{v}_{O_2}$: 37 mm Hg ($S\bar{v}_{O_2}$ = 65%)

With this information, the patient's $P_{A_{O_2}}$, Cc_{O_2}, Ca_{O_2}, and $C\bar{v}_{O_2}$ can now be calculated. (Remember: P_{H_2O} represents alveolar water vapor pressure and is always considered to be 47 mm Hg.)

1. $$\begin{aligned} P_{A_{O_2}} &= (P_B - P_{H_2O})F_{I_{O_2}} - Pa_{CO_2}(1.25) \\ &= (750 - 47)0.70 - 43(1.25) \\ &= (703)0.70 - 53.75 \\ &= 492.1 - 53.75 \\ &= 438.35 \text{ mm Hg} \end{aligned}$$
2. $$\begin{aligned} Cc_{O_2} &= (\text{Hb} \times 1.34)^{10} + (P_{A_{O_2}}{}^{11} \times 0.003) \\ &= (13 \times 1.34) + (438.35 \times 0.003) \\ &= 17.42 + 1.315 \\ &= 18.735 \text{ (mL/dL } O_2) \end{aligned}$$
3. $$\begin{aligned} Ca_{O_2} &= (\text{Hb} \times 1.34 \times Sa_{O_2}) + (Pa_{O_2} \times 0.003) \\ &= (13 \times 1.34 \times 0.85) + (50 \times 0.003) \end{aligned}$$

---

[10] It is assumed that the hemoglobin saturation with oxygen in the pulmonary capillary blood is 100 percent or 1.0.

[11] Refer to "Ideal Alveolar Gas Equation" section in Chapter 4.

$$\begin{aligned}
&= 14.807 + 0.15 \\
&= 14.957\ (\text{mL/dL } O_2)
\end{aligned}$$

$$\begin{aligned}
4.\ C\bar{v}_{O_2} &= (\text{Hb} \times 1.34 \times S\bar{v}_{O_2}) + (P\bar{v}a_{O_2} \times 0.003) \\
&= (13 \times 1.34 \times 0.65) + (37 \times 0.003) \\
&= 11.323 + 0.111 \\
&= 11.434\ (\text{mL/dL } O_2)
\end{aligned}$$

Based on these calculations, the patient's degree of pulmonary shunting can now be calculated:

$$\begin{aligned}
\frac{\dot{Q}s}{\dot{Q}_T} &= \frac{Cc_{O_2} - Ca_{O_2}}{Cc_{O_2} - C\bar{v}_{O_2}} \\
&= \frac{18.735 - 14.975}{18.735 - 11.434} \\
&= \frac{3.778}{7.301} \\
&= 0.517
\end{aligned}$$

Thus, in this case, 51.7 percent of the patient's pulmonary blood flow is perfusing lung tissue that is not being ventilated.

Today, most critical care units have programmed the oxygen transport calculations into inexpensive personal computers. What was once a time-consuming, error-prone task is now quickly and accurately performed.

Clinical Significance of Pulmonary Shunting

Pulmonary shunting below 10 percent reflects normal lung status. A shunt between 10 and 20 percent is indicative of an intrapulmonary abnormality but is seldom of clinical significance. Pulmonary shunting between 20 and 30 percent denotes significant intrapulmonary disease and may be life-threatening in patients with limited cardiovascular function.

When the pulmonary shunting is greater than 30 percent, a potentially life-threatening situation exists and aggressive cardiopulmonary supportive measures are almost always necessary.

Calculating the degree of pulmonary shunting is not reliable in patients who demonstrate (1) a questionable perfusion status, (2) a decreased myocardial output, or (3) an unstable oxygen consumption demand. This is because these conditions directly affect a patient's Ca_{O_2} and $C\bar{v}_{O_2}$ values—two major components of the shunt equation.

Hypoxia

Hypoxemia versus Hypoxia

Hypoxemia refers to an abnormally low arterial oxygen tension (PA_{O_2}) and is frequently associated with *hypoxia,* which is an inadequate level of tissue oxygenation (see following discussion). Although the presence of hypoxemia strongly suggests tissue hypoxia, it does not necessarily mean the absolute existence of tissue hypoxia. For example, the reduced level of oxygen in the arterial blood may be offset by an increased cardiac output. Hypoxemia is commonly classified as mild, moderate, or severe hypoxemia (Table 6–11). As will be discussed in Chapter 9, the presence of mild hypoxemia generally stimulates the oxygen peripheral chemoreceptors to increase the patient's breathing rate and heart rate.

Hypoxia refers to low or inadequate oxygen for aerobic cellular metabolism. Hypoxia is characterized by tachycardia, hypertension, peripheral vasoconstriction, dizziness, and mental confusion. There

TABLE 6-11 Hypoxemia Classification*

Classification	Pa_{O_2} (mm Hg) (Rule of Thumb)
Normal	80–100
Mild hypoxemia	60–80
Moderate hypoxemia	40–60
Severe hypoxemia	<40

*The hypoxemia classifications presented in this table are generally accepted classifications. Minor variations on these values are found in the literature. In addition, a number of clinical factors often require some changes in these values (e.g., a Pa_{O_2} less than 60 mm Hg may be called severe in the patient with a very low blood volume or anemia). Nevertheless, the hypoxemia classifications and Pa_{O_2} range(s) provided in this table are useful guidelines.

are four main types of hypoxia: (1) hypoxic hypoxia, (2) anemic hypoxia, (3) circulatory hypoxia, and (4) histotoxic hypoxia (Table 6–12).

When hypoxia exists, alternate anaerobic mechanisms are activated in the tissues that produce dangerous metabolites—such as lactic acid—as a waste product. Lactic acid is a nonvolatile acid and causes the pH to decrease.

Hypoxic Hypoxia

Clinically, hypoxic hypoxia (also called hypoxemic hypoxia) refers to the condition in which there is inadequate oxygen at the tissue cells caused by low arterial oxygen tension (Pa_{O_2}). Common causes of a decreased Pa_{O_2}

TABLE 6-12 Types of Hypoxia

Hypoxia	Descriptions	Common Causes
Hypoxic hypoxia (also called hypoxemic hypoxia)	Inadequate oxygen at the tissue cells caused by low arterial oxygen tension (Pa_{O_2})	Low $P_{A_{O_2}}$ caused by: • Hypoventilation • High altitude Diffusion impairment • Interstitial fibrosis • Interstitial lung disease • Pulmonary edema • Pneumoconiosis Ventilation-perfusion mismatch Pulmonary shunting
Anemic hypoxia	Pa_{O_2} is normal, but the oxygen-carrying capacity of hemoglobin is inadequate	Decreased hemoglobin concentration • Anemia • Hemorrhage Abnormal hemoglobin • Carboxyhemoglobin • Methemoglobin
Circulatory hypoxia (also called stagnant or hypoperfusion hypoxia)	Blood flow to the tissue cells is inadequate; thus, oxygen is not adequate to meet tissue needs	Slow or stagnant (pooling) peripheral blood flow Arterial venous shunts
Histotoxic hypoxia	Impaired ability of the tissue cells to metabolize oxygen	Cyanide poisoning

are (1) a low alveolar oxygen tension ($P_{A_{O_2}}$), (2) diffusion defects, (3) ventilation-perfusion mismatches, and (4) pulmonary shunting—either absolute or relative shunts. The following sections describe the common causes of hypoxic hypoxia in more detail.

Low Alveolar Oxygen Tension (Decreased $P_{A_{O_2}}$)

Because the arterial oxygen pressure (Pa_{O_2}) is determined by the alveolar oxygen pressure ($P_{A_{O_2}}$), any condition that leads to a decreased $P_{A_{O_2}}$ will result in a reduction of the patient's Pa_{O_2}—and, subsequently, to an inadequate Ca_{O_2}. Common causes of a low $P_{A_{O_2}}$ include (1) hypoventilation and (2) high altitudes.

Hypoventilation is caused by numerous conditions, such as chronic obstructive pulmonary disease, central nervous system depressants (e.g., drug overdose), head trauma, and neuromuscular disorders (e.g., amyotrophic lateral sclerosis [ALS], muscular dystrophies, head injuries, myasthenia gravis or Guillain–Barré syndrome).

High altitude can cause hypoxic hypoxia to develop. This is because the barometric pressure progressively decreases as altitude increases. As the barometric pressure decreases, the atmospheric oxygen tension (Po_2) also decreases. In other words, the higher the altitude, the lower the oxygen pressure (see Figures 2-4 and 2-6). Thus, the higher an individual hikes up a mountain, the lower the oxygen pressure (Po_2) the person is inhaling—which, in turn, leads to a decreased $P_{A_{O_2}}$ and Pa_{O_2}.

Diffusion Defects

Diffusion defects are abnormal anatomic alterations of the lungs that result in an impedance of oxygen transfer across the alveolar-capillary membrane (see Figures 4-4 and 4-8). When a diffusion defect is present, the time available for oxygen equilibrium between the alveolus and pulmonary capillary is not adequate. This condition is referred to as diffusion limited (see Figure 4-11). Common causes of diffusion defects include chronic interstitial lung diseases (pneumoconiosis), pulmonary edema, emphysema, pneumonia, and alveolar collapse (atelectasis) (see Figure 4-12).

Ventilation-Perfusion ($\dot{V}/\dot{Q}$ Ratio) Mismatch

When the pulmonary capillary blood is in excess of the alveolar ventilation, a decreased $\dot{V}/\dot{Q}$ ratio is said to exist. This condition causes pulmonary shunting, which in turn causes the Pa_{O_2} and Ca_{O_2} to decrease. Common causes of a decreased $\dot{V}/\dot{Q}$ ratio include chronic obstructive pulmonary disease, pneumonia, and pulmonary edema. The effects of different $\dot{V}/\dot{Q}$ relationships are discussed in greater detail in Chapter 8.

Pulmonary Shunting

The end result of pulmonary shunting and venous admixture is a decreased Pa_{O_2} and Ca_{O_2} (see Figures 6-16 and 6-17).

Anemic Hypoxia

In this type of hypoxia, the oxygen tension in the arterial blood is normal but the oxygen-carrying capacity of the blood is inadequate. This form of hypoxia can develop from (1) a low amount of hemoglobin in the blood or (2) a deficiency in the ability of hemoglobin to carry oxygen, as occurs in carbon monoxide poisoning or methemoglobinemia.

Anemic hypoxia develops in carbon monoxide poisoning because the affinity of carbon monoxide for hemoglobin is about 210 times greater than that of oxygen. As carbon monoxide combines with hemoglobin, the ability of hemoglobin to carry oxygen diminishes and tissue hypoxia may ensue. In methemoglobinemia, iron atoms in the hemoglobin are oxidized to the ferric state, which in turn eliminates the hemoglobin's ability to carry oxygen. Increased cardiac output is the main compensatory mechanism for anemic hypoxia.

Clinical Connection 6-7

Oxygen Bars—REALLY! People Actually Pay Money for This Activity![12]

During the late 1990s, oxygen bars started appearing throughout the United States at shopping mall kiosks, health spas, casinos, and actual neighborhood bars (Figure 6–18). The purpose of an oxygen bar is to sell oxygen to anyone—at any age—for recreational purposes via a nasal cannula. To enhance the experience, the customer can add a flavored scent—such as, peppermint, bayberry, cranberry, or wintergreen. An oxygen session usually lasts from 5 to 20 minutes and costs about $1.00 per minute. Although most oxygen bars claim to provide their clientele with about 95 percent oxygen, the actual oxygen percentage is most likely between 35 and 40 percent (room air is about 21 percent).

Oxygen bar promoters claim the benefits of inhaling enriched concentrations of oxygen boost energy, reduce stress, enhance the immune system, increase concentration and alertness, reduce the effects of sinus problems, diminish hangovers and headaches, and improve sleep. Despite all these claims, there is no scientific proof that supports that individuals with healthy lungs gain any real benefit from breathing supplemental oxygen. In fact, some medical experts feel using oxygen recreationally is just bad medicine.

According to the federal Food, Drug, and Cosmetic Act, any type of oxygen is considered a drug and, as such, is only to be delivered by licensed personnel under the supervision of a physician and only with a prescription to do so. Although oxygen bars violate U.S. Food and Drug Administration (FDA) regulations, the agency allows regulatory discretion by permitting the individual state boards of licensing to enforce—or not to enforce—the requirements pertaining to the dispensing of oxygen. So, while many states allow oxygen bars and others discourage them by requiring strict compliance with the law, technically operating an oxygen bar is illegal under federal regulations.

While there is no evidence that inhaling low concentrations of oxygen can be dangerous to the normal individual's health, people with certain medical conditions—such as chronic obstructive pulmonary disease—are another matter. Too much oxygen in these patients can be dangerous because it suppresses their hypoxic drive and suppresses ventilation. Similarly, supplemental oxygen is contraindicated in patients being treated with bleomycin for certain types of cancer. In addition, oxygen bars usually produce certain oxygen flavors by bubbling oxygen through containers of aromatic oil solutions and then pumping the vaporized scent to the customer via a nasal cannula. Inhaling an oily substance can lead to a serious inflammation of the lungs—a condition known as **lipoid pneumonia**.

FIGURE 6-18 Oxygen bars.

O2
OXYGEN BAR
Oxygen Bar & Spa

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[12] See Clinical Connection 4–7 for a similar discussion regarding misinformation.

Clinical Connection 6-7, Continued

Even if an oil-free aromatic substance is used, the general maintenance and sterility of the bubbling equipment cannot be guaranteed. Thus, the inhalation of bacteria and a subsequent lung infection is a real possibility. Finally, even though oxygen does not burn, it strongly fuels the combustion process. Smoking or other sources of an open flame anywhere near oxygen can be extremely dangerous.

To further burst the oxygen bar bubble, consider the following facts presented earlier in this chapter: Recall how oxygen is transported to the tissue cells—that is, the total oxygen content of the arterial blood (CaO_2) equation:

$$CaO_2 = (Hb \times 1.34 \times SaO_2) + (PaO_2 \times 0.003)$$

As presented in this formula, the majority of oxygen is carried on the hemoglobin (Hb). In fact, in the normal individual breathing room air (21 percent oxygen), approximately 95 to 97 percent of the total oxygen content is transported to the tissue cells via the hemoglobin. Normally, the CaO_2 is about 20 mL/dL of blood (see page 260). Only a very small portion of the total oxygen content is transported as dissolved oxygen in the plasma. In short, if the blood hemoglobin is already 95 to 97 percent saturated with oxygen, breathing more oxygen adds little to the total oxygen content.

For example, consider the following: Increasing an individual's partial pressure of arterial oxygen (Pa_{O_2}) to 200 mm Hg (i.e., double normal) only increases the total oxygen content of arterial blood by 0.3 mL per 100 mL of blood (200 × 0.003 = 0.6 on supplemental oxygen; 100 × 0.003 = 0.3 already present from breathing room air). This means there is only a net increase of 0.3. Because normal CaO_2 is approximately 20 mL per 100 mL of blood, the increase of 0.3 mL per 100 mL of blood is an insignificant increase in the total content of oxygen in blood—too small to have a physiologic impact on oxygen delivery to tissues and organs to affect function. To further visualize this concept, review the oxyhemoglobin dissociation curve shown in Figure 6–3. Note that once the individual's SaO_2 is on the flat portion of the oxyhemoglobin dissociation curve (as is found in healthy individuals), only a tiny amount of oxygen is gained at higher oxygen partial pressure levels.

Thus, when applying the well-established facts regarding oxygen transport—including (1) the total oxygen content in arterial blood equation and (2) the visual assistance of the oxyhemoglobin curve—one must conclude that the numerous health benefits touted by the oxygen bar proprietors simply do not have merit. Simple math and calculating the increase in oxygen content in arterial blood as would occur from participating in an oxygen bar show that there is an insignificant increase in oxygen delivery to tissues. In fact, many experts believe that any benefits in using supplemental oxygen by the healthy individual are minimal, at best—and most likely are only associated with the placebo effect.

Clinical Connection 6-8

Hemoglobin and Carbon Monoxide Poisoning

Carbon monoxide (CO) is a colorless, odorless gas produced by all internal combustion engines—including gasoline, diesel, and propane-powered engines. CO is also produced by furnaces; by burning wood, paper, or plastic products; and by welding when carbon dioxide shielding gas is used. CO is also found in cigarette smoke and is produced by kerosene space heaters. CO has an attraction for hemoglobin that is more than 200 times greater than that of oxygen—forming a relatively stable compound called **carboxyhemoglobin (CO_{Hb})**. In essence, CO_{Hb} "blocks" oxygen from binding with hemoglobin.

The more an individual is exposed to CO, the more CO_{Hb} that is formed, which in turn means less oxygen that is being carried by the blood to the tissue cells—a life-threatening situation! At lower exposure levels,

(*Continued*)

Clinical Connection 6-8, Continued

individuals sometimes mistake the symptoms of CO exposure (e.g., headache, dizziness, nausea) as the flu. In addition, the fetus of the smoking pregnant woman can be adversely affected by the CO she inhales.

It should be noted that when a patient is known or suspected to have CO poisoning, a standard pulse oximeter does not correct for the presence of carboxyhemoglobin—it overestimates the true oxygen saturation level. In addition, a standard blood gas analyzer should not be used, because it will give a falsely high Pa_{O_2} and Sa_{O_2} reading. The only way to accurately measure the Pa_{O_2} and Sa_{O_2} in the patient with CO poisoning is by running the patient's blood through a special laboratory machine called a **CO-oximter/hemoximeter**.

Treatment for CO poisoning is 100 percent oxygen, usually by a non-rebreather oxygen mask. (Oftentimes, the respiratory therapist working in the emergency department appropriately "over-oxygenates" the patient who is suspected of CO poisoning—e.g., the fireman or victim overcome by smoke.) One therapeutic strategy used to remove the CO is to place the patient in a hyperbaric oxygen chamber—high P_{O_2} pressures can "knock off" the CO from the Hb, allowing the oxygen to form oxyhemoglobin (Hb_{O_2}).

Circulatory Hypoxia

In *circulatory hypoxia,* also called *stagnant* or *hypoperfusion hypoxia,* the arterial blood that reaches the tissue cells may have a normal oxygen tension and content, but the amount of blood—and, therefore, the amount of oxygen—is not adequate to meet tissue needs. The two main causes of circulating hypoxia are (1) slow or stagnant peripheral blood flow and (2) arterial-venous shunting.

Stagnant (hypoperfusion) hypoxia can occur when the peripheral capillary blood flow is slow or stagnant (*pooling*). This condition can be caused by (1) a decreased cardiac output, (2) vascular insufficiency, or (3) neurochemical abnormalities. When blood flow through the tissue capillaries is sluggish, the time needed for oxygen exchange increases while, at the same time, the oxygen supply decreases. Because tissue metabolism continues at a steady rate, the oxygen pressure gradient between the blood and the tissue cells can become insufficient, causing tissue hypoxia. Stagnant hypoxia is primarily associated with cardiovascular disorders and often occurs in the absence of arterial hypoxemia. It is commonly associated with a decreased $S\bar{v}_{O_2}$.

When arterial blood completely bypasses the tissue cells and moves into the venous system, an *arterial-venous shunt* is said to exist. This condition can also cause tissue hypoxia because arterial blood is prevented from delivering oxygen to the tissue cells. Localized arterial or venous obstruction can cause a similar form of tissue hypoxia because the flow of blood into or out of the tissue capillaries is impeded. Circulatory hypoxia can also develop when the tissues' need for oxygen exceeds the available oxygen supply.

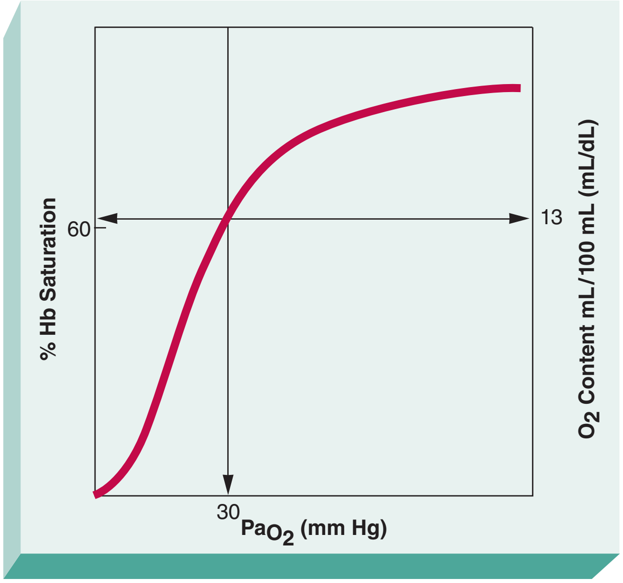
Histotoxic Hypoxia

Histotoxic hypoxia develops in any condition that impairs the ability of tissue cells to utilize oxygen. Cyanide poisoning produces this form of hypoxia. Clinically, the Pa_{O_2} and Ca_{O_2} in the blood are normal, but the tissue cells are extremely hypoxic. The $P\bar{v}_{O_2}$, $C\bar{v}_{O_2}$, and $S\bar{v}_{O_2}$ are elevated because oxygen is not utilized.

Cyanosis

When hypoxemia is severe, signs of cyanosis may develop. *Cyanosis* is the term used to describe the blue-gray or purplish discoloration seen on the mucous membranes, fingertips, and toes whenever the blood in these areas contains at least 5 g/dL of reduced hemoglobin per dL (100 mL). When the normal 14 to 15 g/dL of hemoglobin is fully saturated, the Pa_{O_2} will be about 97 to 100 mm Hg, and there will be about 20 mL/dL

FIGURE 6–19 Cyanosis may appear whenever the blood contains at least 5 g/dL of reduced hemoglobin. In the normal individual with 15 g/dL hemoglobin, a Pa_{O_2} of about 30 mm Hg will produce 5 g/dL of reduced hemoglobin. Overall, however, the hemoglobin is still about 60 percent saturated with oxygen.



of oxygen in the blood. In the patient with cyanosis with one-third (5 g/dL) of the hemoglobin reduced, the Pa_{O_2} will be about 30 mm Hg, and there will be about 13 mL/dL of oxygen in the blood (Figure 6–19). In the patient with polycythemia, however, cyanosis may be present at a Pa_{O_2} well above 30 mm Hg because the amount of reduced hemoglobin is often greater than 5 g/dL in these patients—even when their total oxygen transport is within normal limits (about 20 mL/dL of O_2).

The detection and interpretation of cyanosis are difficult, and there is wide individual variation among observers. The recognition of cyanosis depends on the acuity of the observer, the lighting conditions in the examining room, and the pigmentation of the patient. Cyanosis of the nail beds is also influenced by the temperature because vasoconstriction induced by cold may slow circulation to the point where the blood becomes bluish in the surface capillaries, even though the arterial blood in the major vessels is not oxygen poor.

Clinical Connection 6-9

Blood Doping[13]

Blood doping (also called **blood packing** or **blood boosting)** is the illegal practice of increasing the number of red blood cells (RBCs) in the bloodstream in order to enhance athletic performance. In theory, more RBCs—thus, more hemoglobin—will carry more oxygen to the muscles—thus, giving the athlete an unfair edge during competition. Since the 1970s, blood doping has been commonly associated with Olympic athletes who compete in high-endurance races—such as cycling, long-distance running, or cross-country skiing. In 1985, the U.S. Olympic Committee banned the practice of blood doping.

In general, blood doping involves the harvesting of the athlete's own blood a few weeks before

(*Continued*)

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[13] Also see related Clinical Connection 19–1: Hypobaric Sleep and the Athlete in Training.

Clinical Connection 6-9, Continued

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competition. The blood is usually processed down to a high concentration of RBCs and then stored. A day or two before the sports event, the stored RBCs are then re-injected into the athlete's bloodstream—thus, increasing the overall number of RBCs (and hemoglobin).

More recently, the advances in medicine have led to an entirely new form of blood doping—the use of the **hormone erythropoietin (EPO)**. EPO is a naturally occurring hormone that stimulates the formation of RBCs. As the science of sports medicine continues to advance, the issues associated with blood doping (e.g., ethics, health, and competitive fairness) will likely be debated for many years to come.

Finally, in addition to being illegal for Olympic competition, there are many negative consequences associated with the practice of blood doping—including possible transfusion problems (e.g., infections, receiving tainted blood, hepatitis, or AIDS), increased blood viscosity, increased blood pressure, heart attack, blood clots, stroke, and pulmonary embolism. On the other hand, it is legal for athletes to train in areas of high altitude—such as Denver, Colorado. Such training may stimulate a natural increase of RBCs because the atmospheric pressure of oxygen is less at high altitudes. In other words, the body generates more RBCs to compensate for the decreased arterial oxygen content. Likewise, athletes who compete in Denver will be at a disadvantage if their training occurred at sea level.

Carbon Dioxide Transport

An understanding of carbon dioxide (CO_2) transport is also essential to the study of pulmonary physiology and to the clinical interpretation of arterial blood gases (see Table 6–1). To fully comprehend this subject, a basic understanding of (1) the six ways carbon dioxide is transported from the tissues to the lungs, (2) how carbon dioxide is eliminated at the lungs, and (3) the carbon dioxide dissociation curve is necessary.

The Six Ways Carbon Dioxide Is Transported to the Lungs

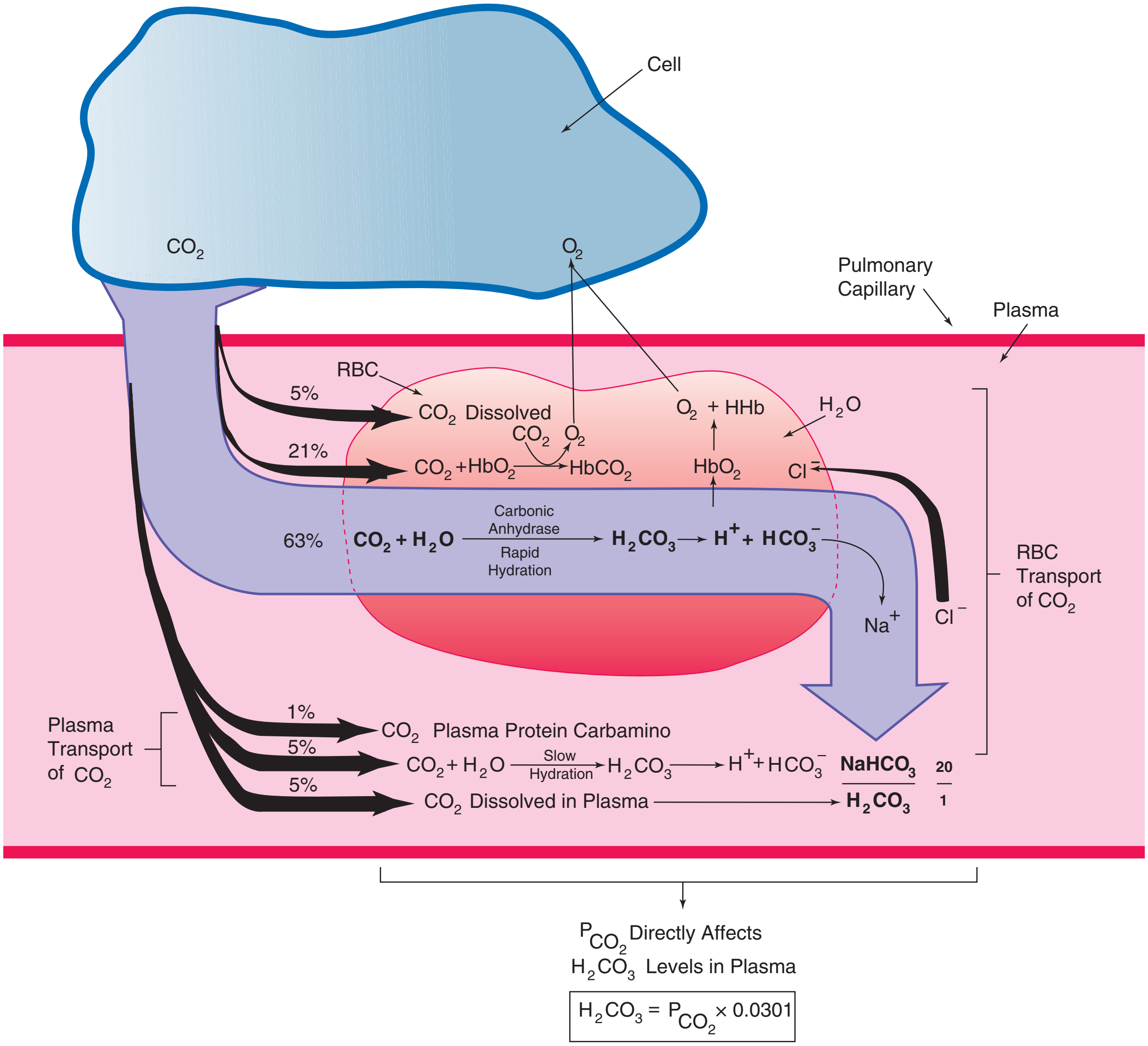
At rest, the metabolizing tissue cells consume about 250 mL of oxygen and produce about 200 mL of carbon dioxide each minute. The newly formed carbon dioxide is transported from the tissue cells to the lungs by six different mechanisms—three are in the plasma and three in the red blood cells (RBCs) (Figure 6–20).

In Plasma

- Carbamino compound (bound to protein)
- Bicarbonate
- Dissolved CO_2

Although relatively insignificant, about 1 percent of the CO_2 that dissolves in the plasma chemically combines with free amino groups of protein molecules and forms a **carbamino compound** (see Figure 6–20).

FIGURE 6-20 How CO_2 is converted to HCO_3^- at the tissue sites. Most of the CO_2 that is produced at the tissue cells is carried to the lungs in the form of HCO_3^-.


Cell
CO2
O2
Pulmonary Capillary
Plasma
RBC
5%
CO2 Dissolved
CO2 O2
21%
CO2 + HbO2 → HbCO2
O2 + HHb
HbO2
H2O
Cl−
63%
CO2 + H2O
Carbonic Anhydrase
Rapid Hydration
H2CO3 → H+ + HCO3−
Na+
Cl−
RBC Transport of CO2
Plasma Transport of CO2
1%
CO2 Plasma Protein Carbamino
5%
CO2 + H2O
Slow Hydration
H2CO3 → H+ + HCO3−
NaHCO3
20
5%
CO2 Dissolved in Plasma
H2CO3
1
PCO2 Directly Affects H2CO3 Levels in Plasma
H2CO3 = PCO2 × 0.0301

Approximately 5 percent of the CO_2 that dissolves in the plasma ionizes as **bicarbonate** (HCO_3^-). Initially, CO_2 combines with water in a process called *hydrolysis*. The hydrolysis of CO_2 and water forms carbonic acid (H_2CO_3), which in turn rapidly ionizes into HCO_3^- and H^+ ions.

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows HCO_3^- + H^+$$

The resulting H^+ ions are buffered by the plasma proteins. The rate of this hydrolysis reaction in the plasma is very slow and, therefore, the amount of HCO_3^- and H^+ ions that form by this mechanism is small.

Dissolved carbon dioxide (CO_2) in the plasma accounts for about 5 percent of the total CO_2 released at the lungs. It is this portion of the CO_2 transport system in the venous blood that is measured to assess the patient's partial pressure of CO_2 (P_{CO_2}) (see Table 6–13).

Note also that the concentration of H_2CO_3 that forms in the plasma is about 1/1000 that of the physically dissolved CO_2 (P_{CO_2}) and, therefore, is proportional to the partial pressure of the CO_2. The H_2CO_3 concentration can be determined by multiplying the partial pressure of CO_2 by the factor 0.03.

TABLE 6-13 Carbon Dioxide (CO_2) Transport Mechanisms

CO_2 Transport Mechanisms	Approx. % of Total CO_2 Transported to the Lungs	Approx. Quantity of Total CO_2 Transported to the Lungs (mL/min)
In Plasma		
Carbamino compound	1	2
Bicarbonate	5	10
Dissolved CO_2	5	10
In Red Blood Cells		
Dissolved CO_2	5	10
Carbamino-Hb	21	42
Bicarbonate	63	126
Total	**100**	**200**

For example, a P_{CO_2} of 40 mm Hg generates an H_2CO_3 concentration of 1.2 mEq/L ($0.03 \times 40 = 1.2$) (see Figure 6–20).

In Red Blood Cells

- Dissolved CO_2
- Carbamino-Hb
- Bicarbonate

Dissolved carbon dioxide (CO_2) in the intracellular fluid of the red blood cells accounts for about 5 percent of the total CO_2 released at the lungs (see Figure 6–20).

About 21 percent of the CO_2 combines with hemoglobin to form a compound called **carbamino-Hb**. The O_2 that is released by this reaction is available for tissue metabolism (see Figure 6–20).

Most of the CO_2 (about 63 percent) is transported from the tissue cells to the lungs in the form of HCO_3^-. The major portion of the dissolved CO_2 that enters the RBCs is converted to HCO_3^- by the following reactions (see Figure 6–20):

1. The bulk of dissolved CO_2 that enters the RBC undergoes hydrolysis according to the following reaction (CA = carbonic anhydrase):

   $$CO_2 + H_2O \overset{CA}{\leftrightarrows} H_2CO_3 \leftrightarrows H^+ + HCO_3^-$$

   This reaction, which is normally a very slow process in the plasma, is greatly enhanced in the RBC by the enzyme carbonic anhydrase.

2. The resulting H^+ ions are buffered by the reduced hemoglobin.
3. The rapid hydrolysis of CO_2 causes the RBC to become saturated with HCO_3^-. To maintain a concentration equilibrium between the RBC and plasma, the excess HCO_3^- diffuses out of the RBC.
4. Once in the plasma, the HCO_3^- combines with sodium (Na^+), which is normally in the plasma in the form of sodium chloride (NaCl). The HCO_3^- is then transported to the lungs as $NaHCO_3$ in the plasma of the venous blood.
5. As HCO_3^- moves out of the RBC, the Cl^- (which has been liberated from NaCl) moves into the RBC to maintain electric neutrality. This movement is known as the **chloride shift**, or the **Hamburger phenomenon**,

or as an **anionic shift to equilibrium**. During the chloride shift, some water moves into the RBC to preserve the osmotic equilibrium. This action causes the RBC to slightly swell in the venous blood.

6. In the plasma, the ratio of HCO_3^- and H_2CO_3 is normally maintained at 20:1. This ratio keeps the blood pH level within the normal range of 7.35 to 7.45. The pH of the blood becomes more alkaline as the ratio increases and less alkaline as the ratio decreases.

Carbon Dioxide Elimination at the Lungs

As shown in Figure 6–21, as the venous blood enters the alveolar capillaries, the chemical reactions occurring at the tissue level are reversed. These chemical processes continue until the CO_2 pressure is equal throughout the entire system. Table 6–13 summarizes the percentage and quantity of the total CO_2 that is transported from the tissue cells to the lungs by the six CO_2 mechanisms each minute.

FIGURE 6-21 How HCO_3^- is transformed back into CO_2 and eliminated in the alveoli.

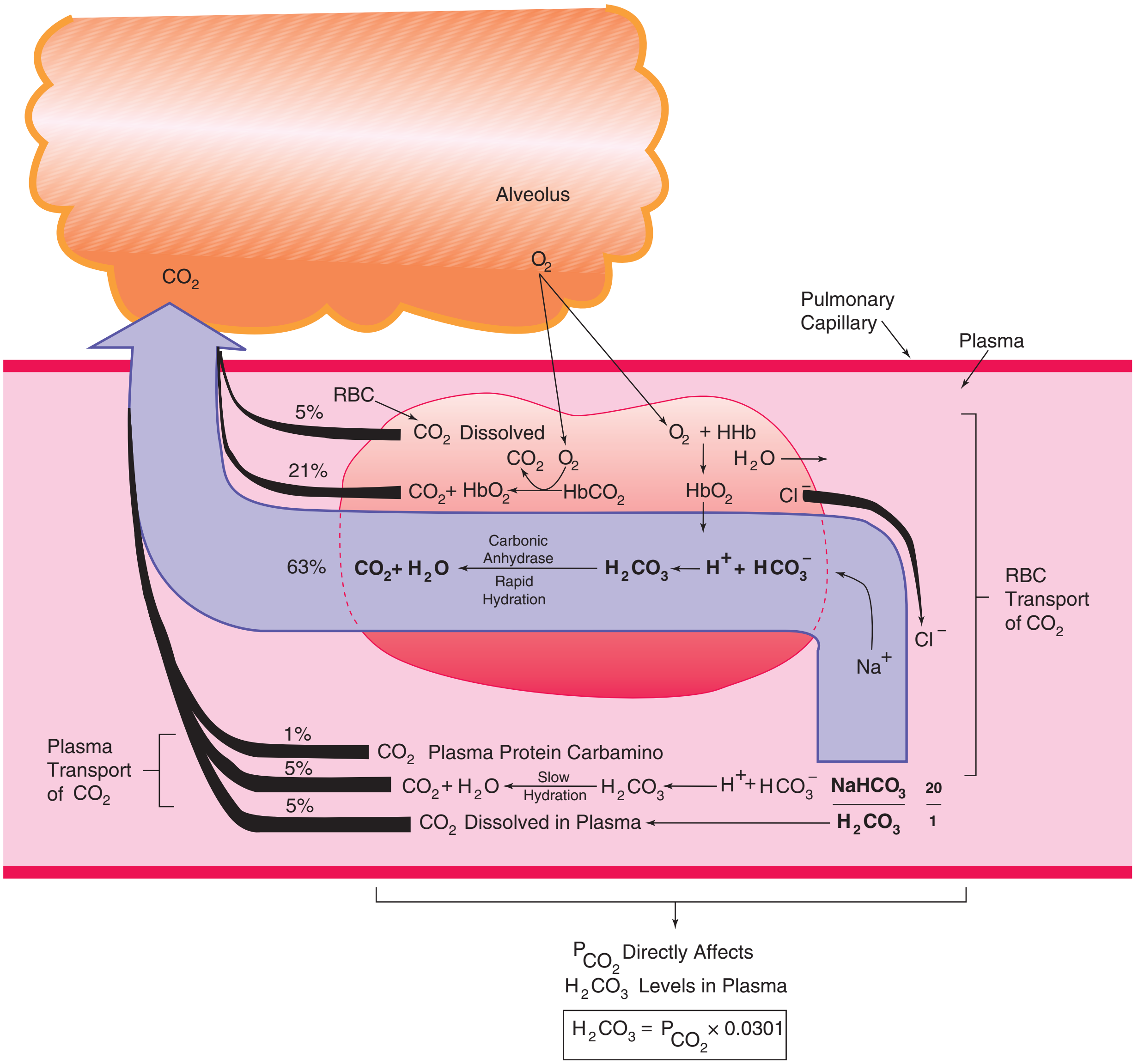
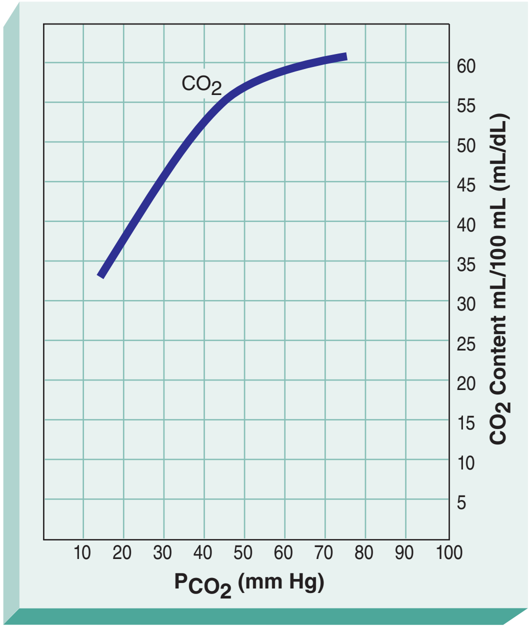

Alveolus
CO2
O2
Pulmonary Capillary
Plasma
RBC
5%
CO2 Dissolved
O2 + HHb
CO2 O2
H2O
21%
CO2 + HbO2
HbCO2
HbO2
Cl−
63%
CO2 + H2O
Carbonic Anhydrase
Rapid Hydration
H2CO3
H+ + HCO3−
Cl−
Na+
RBC Transport of CO2
Plasma Transport of CO2
1%
CO2 Plasma Protein Carbamino
5%
CO2 + H2O
Slow Hydration
H2CO3
H+ + HCO3−
NaHCO3
20
5%
CO2 Dissolved in Plasma
H2CO3
1
PCO2 Directly Affects H2CO3 Levels in Plasma
H2CO3 = PCO2 × 0.0301

FIGURE 6-22 Carbon dioxide dissociation curve.



Carbon Dioxide Dissociation Curve

Similar to the oxyhemoglobin dissociation curve, the loading and unloading of CO_2 in the blood can be illustrated in graphic form (Figure 6–22). Unlike the S-shaped oxygen dissociation curve, however, the carbon dioxide curve is almost linear. This means that compared with the oxyhemoglobin dissociation curve, there is a more direct relationship between the partial pressure of CO_2 (P_{CO_2}) and the amount of CO_2 (CO_2 content) in the blood. For example, when the P_{CO_2} increases from 40 to 46 mm Hg between the arterial and venous blood, the CO_2 content increases by about 5 mL/dL (Figure 6–23). The same partial pressure change of oxygen would increase the oxygen content only by about 2 mL/dL (see Figure 6–3).

FIGURE 6-23 Carbon dioxide dissociation curve. An increase in the P_{CO_2} from 40 to 46 mm Hg raises the CO_2 content by about 5 mL/dL. P_{CO_2} changes have a greater effect on CO_2 content levels than P_{O_2} changes have on O_2 levels.

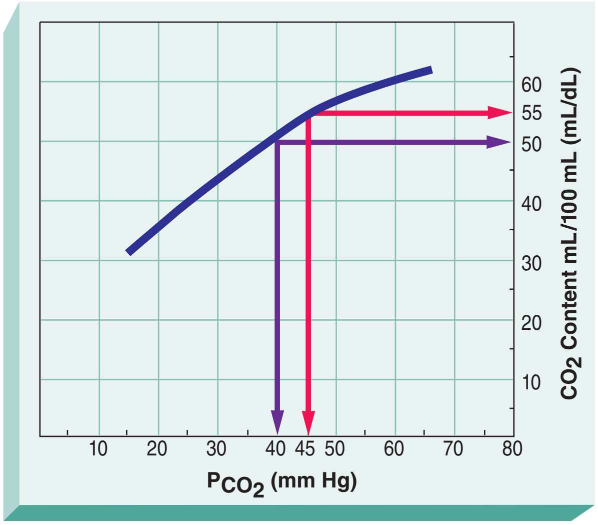
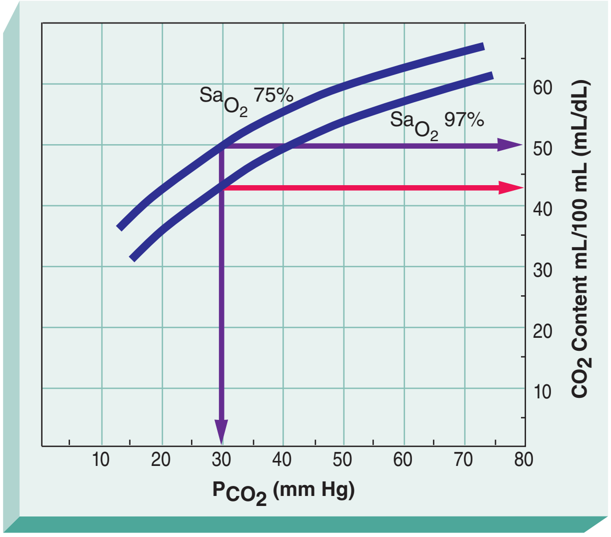


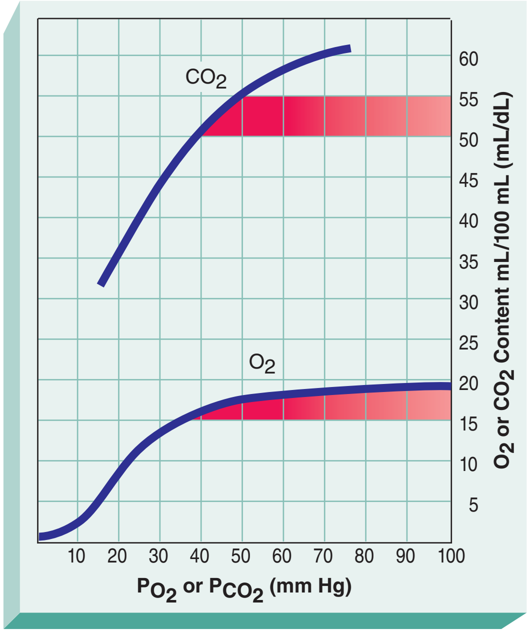
FIGURE 6–24 Carbon dioxide dissociation curve at two different oxygen/hemoglobin saturation levels (Sa_{O_2} of 97 and 75 percent). When the saturation of O_2 increases in the blood, the CO_2 content decreases at any given P_{CO_2}. This is known as the Haldane effect.



The level of saturation of hemoglobin with oxygen (e.g., Sa_{O_2} or $S\bar{v}_{O_2}$) also affects the carbon dioxide dissociation curve. When the hemoglobin is 97 percent saturated with oxygen, for example, there is less CO_2 content for any given P_{CO_2} than if the hemoglobin is, say, 75 percent saturated with oxygen (Figure 6–24). The fact that deoxygenated blood enhances the loading of CO_2 is called the **Haldane effect**. Note also that the Haldane effect works the other way—that is, the oxygenation of blood enhances the unloading of CO_2.

Figure 6–25 compares both the oxygen and the carbon dioxide dissociation curves in terms of partial pressure, content, and shape.

FIGURE 6–25 Comparison of the oxygen and carbon dioxide dissociation curves in terms of partial pressure, content, and shape.



Clinical Connection 6-10

Capnography Ventilation vs. Oxygenation (Pulse Oximetry)[14]

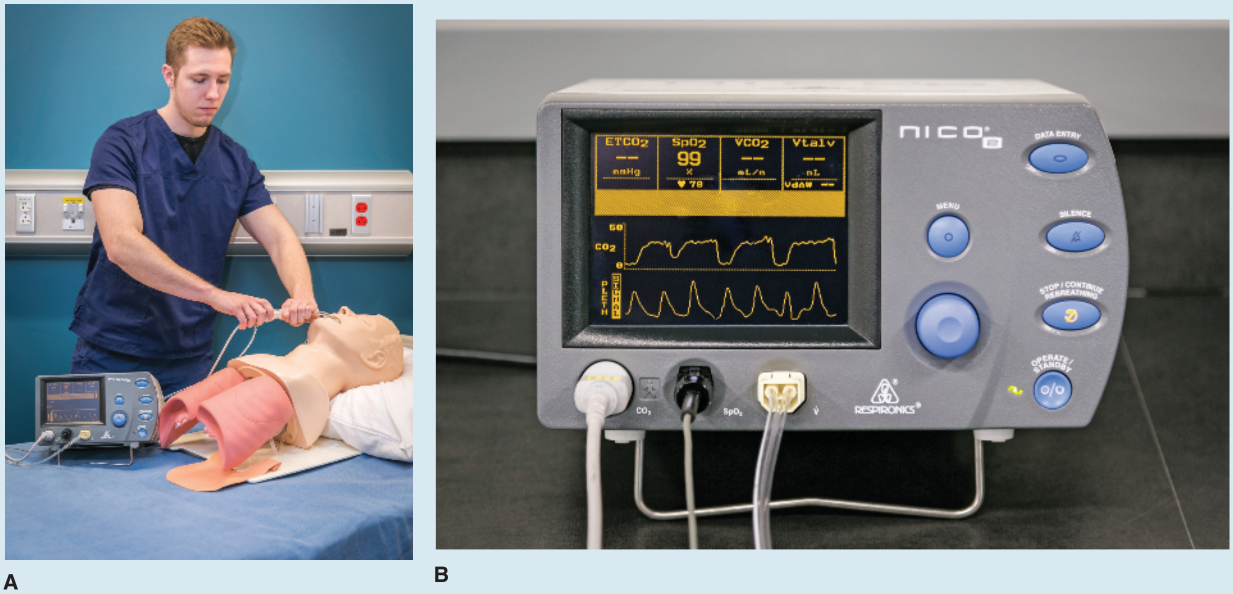
Capnometry is the noninvasive measurement of carbon dioxide (CO_2) levels in the proximal airway during inspiration and expiration. A **capnometer** is the monitoring device that is used to measure and numerically display the exhaled carbon dioxide (Figure 6–26). **Capnography** is the graphic waveform display of CO_2 partial pressures during exhalation and inhalation (Figure 6–27). Capnography offers the advantages of providing instant information as well as being noninvasive. Carbon dioxide may also be measured by an arterial blood gas (ABG) analysis; however, this requires an invasive needle puncture and time for results to be measured through an analyzer—perhaps located in a laboratory some distance from the patient.

Clinically, uses of capnography include ventilation monitoring during general anesthesia, mechanical ventilation, and the confirmation of proper placement of an endotracheal tube. In fact, the **American Heart Association** (**AHA**) **Guidelines for Cardiopulmonary Resuscitation and Emergency Cardiovascular Care**, **Part 8.1, "Adjuncts for Airway Control and Ventilation—Overview of Airway Management**," states the following:

> Continuous waveform capnography is recommended in addition to clinical assessment as the most reliable method of confirming and monitoring correct placement of an endotracheal tube. … Providers should observe a persistent capnographic waveform with ventilation to confirm and monitor endotracheal tube placement in the field, in the transport vehicle, on arrival at the hospital, and after any patient transfer to reduce the risk of unrecognized tube misplacement or displacement.

It is interesting to note that "the most reliable method of confirming and monitoring correct placement of an endotracheal tube" is by the capnographic waveform—and not by

FIGURE 6–26 Capnometer. **A.** Respiratory therapy student setting up a capnometer in a simulated lab setting. **B.** Closeup of the capnometer. (Also see Clinical Connection 8–3: Capnography.)



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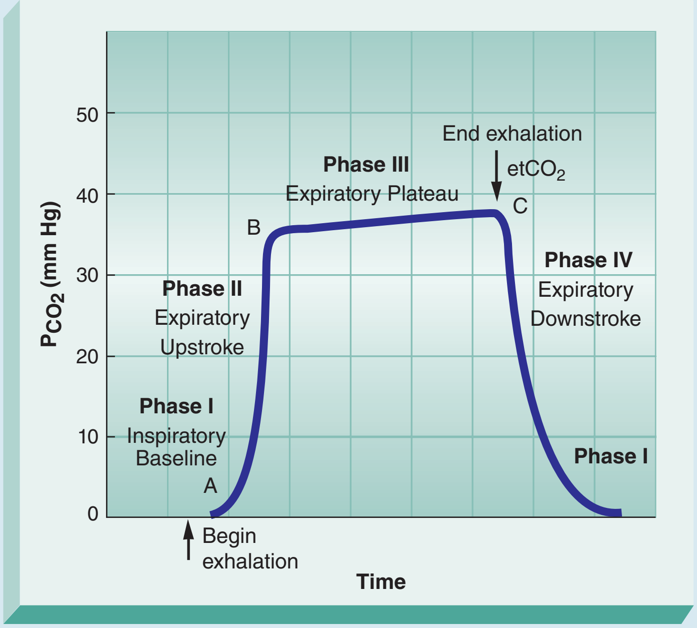
[14] Also see Clinical Connection 8–3: Capnography.

Clinical Connection 6-10, Continued

FIGURE 6-27 Normal single-breath capnogram. **Phase I (A)**. The first part, exhalation, is composed of pure dead space gas from the airways. Initially, the expired PCO_2 level is 0 mm Hg. **Phase II (A to B)**. As exhalation continues, alveolar gas begins to mix with the dead space gas in the airways, resulting in a rapid increase in the expired PCO_2 level—in this case, about 33 mm Hg. **Phase III (B to C)**. The CO_2 concentration then reaches a plateau and represents alveolar gas. A gas sample at "C" is called end-tidal carbon dioxide ($etCO_2$). The sudden downstroke immediately after "C," and return to the baseline, represents the normal inhalation of fresh gas with no CO_2. Normal values of $etCO_2$ are 35–37 mmHg, and in normal lungs, the $etCO_2$ approximates the arterial CO_2 concentration in the blood with a value that is usually lower by 2–5 mm Hg. (Also see Clinical Connection 8–3: Capnography.)



pulse oximetry (see Clinical Connection 6–3: The Pulse Oximeter).

Why is this? Especially since pulse oximetry is widely available and utilized. Capnography measures the patient's ventilatory status on a breath-by-breath, moment-to-moment, real-time basis. Each breath yields a capnographic waveform in which exhaled CO_2 levels can be seen and verified as the measure of ventilation and the exchange of gas—this will only occur if the endotracheal tube is properly placed in the trachea and not fatally misplaced in the esophagus.

In contrast, the pulse oximeter only measures the patient's current oxygenation saturation—not the patient's ventilatory status. Although integrally linked, ventilation and oxygenation are different gas exchange functions. Measuring oxygenation by pulse oximetry does not equate to the measurement of ventilation. In addition, the use of a pulse oximeter has these limitations: When the patient's oxygenation level is on the upper, flat portion of the oxyhemoglobin dissociation curve (especially if receiving 100 percent oxygen), the pulse oximeter may be relatively slow in responding to remarkable oxygenation changes (see Figure 6–3).

Meanwhile, the patient may not be ventilated adequately—or, perhaps, at all—as the providers wait to recognize this unfortunate situation with the relatively slow fall of the pulse oximeter. Remember: Hypoxemia follows (although the response may not always be immediate) conditions such as hypoventilation, apnea, or a misplaced endotracheal tube. Thus, seconds—and, perhaps, minutes—may pass in order for the pulse oximeter to reflect a

(*Continued*)

Clinical Connection 2-10, Continued

possible life-threatening hypoxemia. Relying on the pulse oximeter alone can decrease the margin of patient safety. It should also be noted that hypovolemia, vasoconstriction, peripheral vascular disease, carbon monoxide poisoning, or nail polish may also cause false pulse oximeter readings.

Finally, even though ventilation and oxygenation are often—incorrectly—considered the same thing, they are not! Ventilation and oxygenation are based on two entirely different physiologic processes. **Ventilation** is the movement of gas in and out of the lungs. It is the process that moves gases between the external environment and the alveoli. Ventilation is the mechanism by which oxygen is carried from the atmosphere to the alveoli and by which carbon dioxide is carried from the alveoli to the atmosphere. **Oxygenation**, in contrast, is the process of oxygen being taken into the lungs and carried to the alveoli, where it diffuses passively into the pulmonary capillary blood. An individual's actual oxygenation status is the amount of oxygen being carried in the arteries to the tissue cells.

Thus, other than an invasive arterial blood gas analysis, the pulse oximeter represents the principal means of assuring the patient's saturation of peripheral oxygen (Sp_{O_2}), and the capnometer represents the primary means of confirming the patient's ventilatory status. While a pulse oximeter provides valuable data regarding a patient's oxygenation status, it must never be confused with its inability to assess ventilatory status—this is monitored using capnography or the Pa_{CO_2} from an ABG analysis. Therefore, oxygenation measures such as pulse oximetry and Pa_{O_2} assess oxygenation, while measures such as capnometry and Pa_{CO_2} assess ventilation—making oxygenation and ventilation integrally linked but separate gas exchange functions, each requiring its own means of measurement.

Chapter Summary

The understanding of oxygen transport is a fundamental cornerstone to the clinical interpretation of arterial and venous blood gases. Essential components are (1) how oxygen is transported from the lungs to the tissue, including the calculation of the quantity of oxygen that is dissolved in the plasma and bound to hemoglobin; (2) the oxyhemoglobin dissociation nomogram and how it relates to oxygen pressure, percentage of hemoglobin bound to oxygen, oxygen content, and right and left curve shifts; (3) how the following oxygen transport calculations are used to identify the patient's cardiac and ventilatory status: total oxygen delivery, arterial-venous oxygen content difference, oxygen consumption, oxygen extraction ratio, mixed venous oxygen saturation, and pulmonary shunting; and (4) the major forms of tissue hypoxia: hypoxic hypoxia, anemic hypoxia, circulatory hypoxia, and histotoxic hypoxia.

An understanding of carbon dioxide transport is also a fundamental cornerstone to the study of pulmonary physiology and the clinical interpretation of arterial blood gases. Essential components are the transport of carbon dioxide from the tissues to the lungs, including the three ways in which carbon dioxide is transported in the plasma and three ways in the red blood cells, the elimination of carbon dioxide at the lung, and how the carbon dioxide dissociation curves differ from the oxyhemoglobin dissociation curves.

Clinical connections associated with these topics include (1) a case study involving the importance of hemoglobin in oxygen transport, (2) polycythemia, (3) the pulse oximeter and the the Pa_{O_2} and Sa_{O_2} relationship, (4) a case study discussing the significance of a right shift of the oxyhemoglobin dissociation curve, (5) metabolic demand and the variations among animal species, (6) cardiopulmonary resuscitation (CPR), (7) oxygen bars, (8) hemoglobin and carbon monoxide poisoning, (9) blood doping, and (10) capnography vs. oxygenation (pulse oximetry).

1 Clinical Application Case

A 12-year-old girl was a victim of a "drive-by" shooting. She was standing in line outside a movie theater with some friends when a car passed by and someone inside began shooting at three boys standing nearby. Two of the boys died immediately, the third was shot in the shoulder and lower jaw, and the girl was shot in the upper anterior chest. Although she was breathing spontaneously through a non-rebreathing oxygen mask when she was brought to the emergency department 25 minutes later, she was unconscious and had obviously lost a lot of blood. Her clothes were completely soaked with blood.

The patient's skin, lips, and nail beds were blue. Her skin felt cool and clammy. A small bullet hole could be seen over the left anterior chest between the second and third rib at the mid-clavicular line. No exit bullet hole could be seen. Her vital signs were blood pressure—55/35 mm Hg, heart rate—120 beats/min, and respiratory rate—22 breaths/min. Auscultation of the chest revealed normal breath sounds. A portable chest X-ray showed that the bullet had passed through the upper portion of the aorta and lodged near the spine. Fortunately, the bullet did not damage her lung.

Her hematocrit was 15 percent and hemoglobin was 4 g/dL. A unit of blood was started immediately, and a pulmonary catheter and arterial line were inserted (Refer to Figure 15–1). Cardiac output was 6 L/min. Arterial blood gas values (on a non-rebreathing oxygen mask) were pH—7.47, Pa_{CO_2}—31 mm Hg, HCO_3^-—23 mEq/L, and Pa_{O_2}—503 mm Hg. Her Sa_{O_2} was 98 percent. At this time, her oxygen indices were assessed (see accompanying Oxygen Transport Study 1).

The patient was rushed to surgery to repair her damaged aorta. Three hours later, she was transferred to the surgical intensive care unit and placed on a mechanical ventilator. The surgery was considered a success, and the patient's parents were relieved to learn that a full recovery was expected. The patient was conscious and appeared comfortable and her skin felt warm and dry. Her vital signs were blood pressure—125/83 mm Hg, heart rate—76 beats/min, respiratory rate—12 breaths/min (i.e., the ventilator rate was set at 12), and temperature 37°C. Auscultation revealed normal bronchovesicular breath sounds.

Oxygen Transport Study 1

D_{O_2}	$\dot{V}_{O_2}$	$C(a-\bar{v})_{O_2}$	O_2ER	$S\bar{v}_{O_2}$	$\dot{Q}s/\dot{Q}_T$
316 mL	214 mL	3.58 mL/dL	68%	32%	3%

Oxygen Transport Study 2

D_{O_2}	$\dot{V}_{O_2}$	$C(a-\bar{v})_{O_2}$	O_2ER	$S\bar{v}_{O_2}$	$\dot{Q}s/\dot{Q}_T$
935 mL	245 mL	5 mL/dL	25%	75%	3%

D_{O_2} = total oxygen delivery; $\dot{V}_{O_2}$ = oxygen consumption; $C(a - \bar{v})_{O_2}$ = arterial-venous oxygen content difference; O_2ER = oxygen extraction ratio; $S\bar{v}_{O_2}$ = mixed venous oxygen saturation; $\dot{Q}s/\dot{Q}_T$ = the amount of intrapulmonary shunting.

A portable chest X-ray showed no cardiopulmonary problems. Laboratory blood work showed a hematocrit of 41 percent and hemoglobin was 12 g/dL. Arterial blood gas values (while on the mechanical ventilation and on an inspired oxygen concentration FI_{O_2} of 0.4) were pH—7.43, Pa_{CO_2}—38 mm Hg, HCO_3^-—24 mEq/L, and Pa_{CO_2}—109 mm Hg. Sa_{O_2} was 97 percent. A second oxygen transport study showed significant improvement (see accompanying Oxygen Transport Study 2). Over the next 4 days, the patient was weaned from the ventilator and transferred from the surgical intensive care unit to the medical ward. A week later the patient was discharged from the hospital.

Discussion

This case illustrates the importance of *hemoglobin* in the oxygen transport system. As a result of the gunshot wound to the chest, the patient lost a great deal of blood—her hemoglobin was only 4 g/dL. Because of the excessive blood loss, the patient was unconscious, cyanotic, and hypotensive, and her skin was cool and damp to the touch. Despite the fact that the patient had an elevated Pa_{O_2} of 503 mm Hg (normal, 80–100 mm Hg) and an Sa_{O_2} of 98 percent in the emergency department, her tissue oxygenation was seriously impaired. In fact, the patient's Pa_{O_2} and Sa_{O_2} in this case were very misleading. Clinically, this was verified by the oxygen transport studies. For example, her D_{O_2} was only 316 mL (normal, about 1000 mL).

(*continued*)

Clinical Application Case 1 (continued)

Furthermore, note that the patient's $\dot{V}_{O_2}$ was 214 mL/min and O_2ER was 68 percent (the normal extraction ratio is 25 percent). In other words, the patient was consuming 68 percent of the D_{O_2} (214 mL of oxygen out of a possible 316 mL of oxygen per minute). Her oxygen reserve was only about 30 percent. If this condition had not been treated immediately, she would not have survived much longer. It should be stressed that the patient's Pa_{O_2} of 503 mm Hg and Sa_{O_2} of 98 percent were very misleading—and dangerous.

2

Clinical Application Case

An 18-year-old woman presented in the emergency department in severe respiratory distress. She was well known to the respiratory care team. She had suffered from asthma all of her life (Figure 6–28). Over the years, she had been admitted to the hospital on numerous occasions, averaging about three admissions per year. Five separate asthmatic episodes had required mechanical ventilation. Although she was usually weaned from the ventilator within 48 hours, on one occasion she was on the ventilator for 7 days. At the time of this admission, it had been more than 4 years since she was last placed on mechanical ventilation.

Upon observation, the patient appeared fatigued and cyanotic, and she was using her accessory muscles of inspiration. She was in obvious respiratory distress. Her vital signs were blood pressure—177/110 mm Hg, heart rate—160 beats/min, and respiratory rate—32 breaths/min and shallow. Her breath sounds were diminished and wheezing could be heard bilaterally. A portable chest X-ray showed that her lungs were hyperinflated and her diaphragm was depressed. Arterial blood gas values on 4 L/min oxygen via cannula were pH—7.25, Pa_{CO_2}—71 mm Hg, HCO_3^-—27 mEq/L, Pa_{O_2}—27 mm Hg, and Sa_{O_2}—42 percent.

Because she was in acute ventilatory failure with severe hypoxemia and was clearly fatigued, the patient was immediately transferred to the intensive care unit, intubated, and placed on mechanical ventilation at a rate of 3 breaths/min. A pulmonary catheter and arterial line were inserted. An intravenous infusion was started and medications to treat her bronchoconstriction were administered. A hemodynamic study showed that her cardiac output ($\dot{Q}_T$) was 6.5 L/min. Her hemoglobin was 13 g/dL. An oxygen transport study was performed at this time (see accompanying Oxygen Transport Study 1).

Oxygen Transport Study 1

D_{O_2}	$\dot{V}_{O_2}$	$C(a-\bar{v})_{O_2}$	O_2ER	$S\bar{v}_{O_2}$	$\dot{Q}s/\dot{Q}_T$
523 mL	314 mL	4.83 mL/dL	58%	24%	47%

Oxygen Transport Study 2

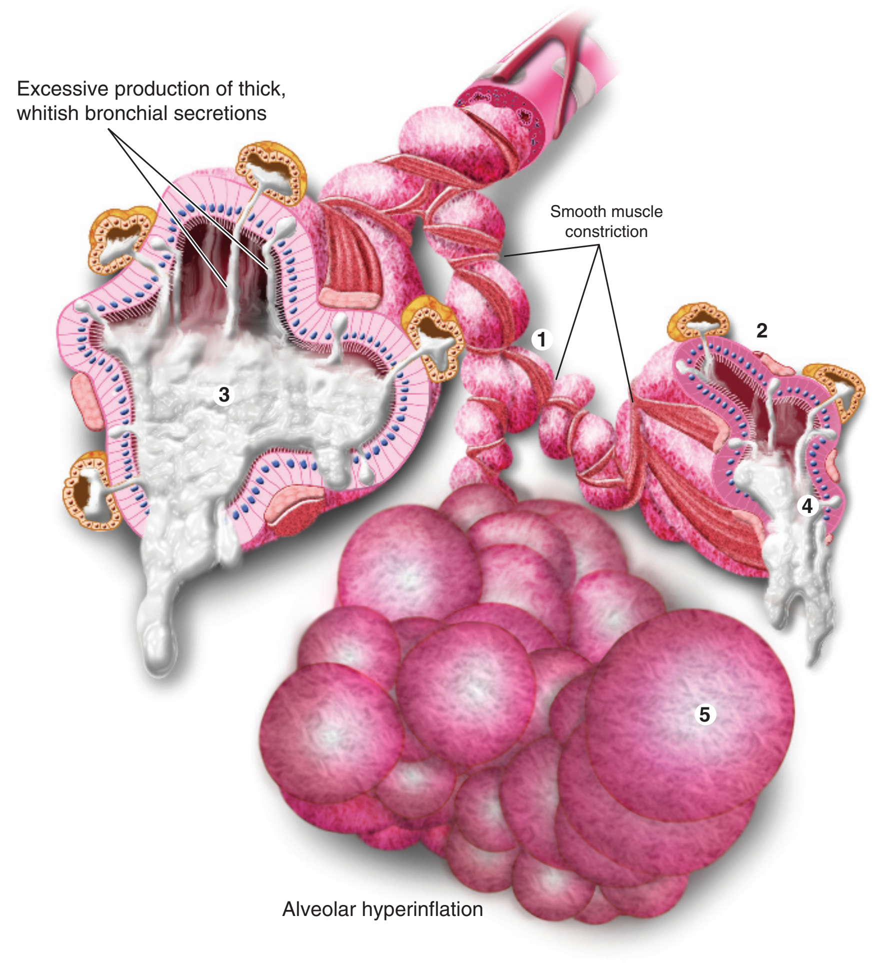
D_{O_2}	$\dot{V}_{O_2}$	$C(a-\bar{v})_{O_2}$	O_2ER	$S\bar{v}_{O_2}$	$\dot{Q}s/\dot{Q}_T$
990 mL	255 mL	5 mL/dL	24%	75%	3%

D_{O_2} = total oxygen delivery; $\dot{V}_{O_2}$ = oxygen consumption; $C(a-\bar{v})_{O_2}$ = arterial-venous oxygen content difference; O_2ER = oxygen extraction ratio; $S\bar{v}_{O_2}$ = mixed venous oxygen saturation; $\dot{Q}s/\dot{Q}_T$ = the amount of intrapulmonary shunting.

Although the patient's first day in the intensive care unit was a stormy one, her asthma progressively improved over the second day. On the morning of the third day, her skin was pink and dry and she was resting comfortably on the mechanical ventilator. Although she was receiving 3 mechanical breaths/min, the patient was breathing primarily on her own. Her vital signs were blood pressure—125/76 mm Hg, heart rate—70 beats/min, and respiratory rate—10 breaths/min (10 spontaneous breaths between the 3 mechanical ventilations per minute). Auscultation revealed normal bronchovesicular breath sounds, and portable chest X-ray no longer showed hyperinflated lungs or a flattened diaphragm. Arterial blood gas values on an inspired oxygen concentration (FI_{O_2}) of 0.25 were pH—7.42, Pa_{CO_2}—37 mm Hg, HCO_3^-—24 mEq/L, Pa_{O_2}—115 mm Hg, and Sa_{O_2}—97 percent. An oxygen transport study was performed at this time (see accompanying Oxygen Transport Study 2). The patient was weaned from the ventilator and was discharged from the hospital the next day.

Clinical Application Case 2 (continued)

FIGURE 6-28 Asthma is characterized by periodic episodes of (1) reversible bronchial smooth muscle constriction, called bronchospasm; (2) airways inflammation, which results in mucosal edema and airways swelling; (3) excessive production of thick, whitish bronchial secretions; (4) mucous plugging; and (5) air trapping and hyperinflation of the alveoli.


Excessive production of thick, whitish bronchial secretions
Smooth muscle constriction
1
2
3
4
5
Alveolar hyperinflation

Discussion

This case illustrates the clinical significance of a *right shift* in the *oxyhemoglobin dissociation curve* on (1) the loading of oxygen on hemoglobin in the lungs and (2) the patient's total oxygen delivery (D_{O_2}). As a result of the asthmatic episode (i.e., bronchial smooth muscle constriction, inflammation, and excessive secretions, the patient's alveolar ventilation was very poor in the emergency department. Clinically, this was verified on chest X-ray showing alveolar hyperinflation and a flattened diaphragm and by arterial blood gas analysis and the oxygen indices.

Note that alveolar "hyperinflation" does not mean the lungs are being excessively ventilated. In fact, they are being underventilated. The lungs become hyperinflated during a severe asthmatic episode because gas is unable to leave the lungs during exhalation. As a result, "fresh" ventilation is impeded on subsequent inspirations. This condition causes the alveolar oxygen ($P_{A_{O_2}}$) to decrease and the alveolar carbon dioxide ($P_{A_{O_2}}$) to increase. As the $P_{A_{O_2}}$ declined, the patient's intrapulmonary shunting ($\dot{Q}_S \div \dot{Q}_T$) and oxygen extraction ratio (O_2ER) increased and total oxygen delivery (D_{O_2}) decreased (see accompanying Oxygen Transport Study 1).

In addition, as shown by the first arterial blood gas analysis, her condition was further compromised by the presence of a decreased pH (7.25) and an increased Pa_{CO_2} (72 mm Hg), which caused the oxyhemoglobin dissociation curve to shift to the right. A right shift of the oxyhemoglobin dissociation curve reduces the ability of oxygen to move across the alveolar-capillary membrane and bond to hemoglobin (see Figure 6–8). Because of this, the patient's hemoglobin saturation was lower than

Clinical Application Case 2 (continued)

expected for a particular Pa_{O_2} level. In this case, the patient's Sa_{O_2} was only 42 percent at a time when the Pa_{O_2} was 27 mm Hg. Normally, when the Pa_{O_2} is 27 mm Hg, the hemoglobin saturation is 50 percent (see Figure 6–6). Thus, it should be emphasized that when additional factors are present that shift the oxyhemoglobin dissociation curve to the right or left, the respiratory therapist should consider these factors in the final analysis of the patient's total oxygenation status.

Review Questions

1. If a patient has a Hb level of 14 g/dL and a Pa_{O_2} of 55 mm Hg (85 percent saturated with oxygen), approximately how much oxygen is transported to the peripheral tissues in each 100 mL of blood?

A. 16 mL/dL
B. 17 mL/dL
C. 18 mL/dL
D. 19 mL/dL

2. When the blood pH decreases, the oxyhemoglobin dissociation curve shifts to the

A. Right and the P_{50} decreases
B. Left and the P_{50} increases
C. Right and the P_{50} increases
D. Left and the P_{50} decreases

3. When shunted, non-reoxygenated blood mixes with reoxygenated blood distal to the alveoli (*venous admixture*), the

1. P_{O_2} of the non-oxygenated blood increases
2. Ca_{O_2} of the reoxygenated blood decreases
3. P_{O_2} of the reoxygenated blood increases
4. Ca_{O_2} of the non-oxygenated blood decreases
   A. 1 only
   B. 4 only
   C. 1 and 2 only
   D. 3 and 4 only

4. The normal arterial HCO_3^- range is

A. 18–22 mEq/L
B. 22–28 mEq/L
C. 28–35 mEq/L
D. 35–45 mEq/L

5. The normal calculated anatomic shunt is about

A. 0.5–1 percent
B. 2–5 percent
C. 6–9 percent
D. 10–12 percent

6. In which of the following types of hypoxia is the oxygen pressure of the arterial blood (Pa_{O_2}) usually normal?

1. Hypoxic hypoxia
2. Anemic hypoxia
3. Circulatory hypoxia
4. Histotoxic hypoxia
   A. 1 only
   B. 2 only
   C. 3 and 4 only
   D. 2, 3, and 4 only

7. If a patient normally has a 12 g/dL Hb, cyanosis will likely appear when

A. 10 g/dL Hb is saturated with oxygen
B. 9 g/dL Hb is saturated with oxygen
C. 8 g/dL Hb is saturated with oxygen
D. 7 g/dL Hb is saturated with oxygen

8. The advantages of polycythemia begin to be offset by the increased blood viscosity when the hematocrit reaches about

A. 30–40 percent
B. 40–50 percent
C. 55–60 percent
D. 60–70 percent

9. Assuming everything else remains the same, when an individual's cardiac output decreases, the

1. $C(a - \bar{v})_{O_2}$ increases
2. O_2ER decreases
3. $\dot{V}_{O_2}$ increases
4. $S\bar{v}_{O_2}$ decreases
   A. 1 only
   B. 4 only

C. 2 and 3 only
D. 1 and 4 only

10. Under normal conditions, the O_2ER is about

A. 10 percent
B. 15 percent
C. 20 percent
D. 25 percent

11. Case Study: Automobile Collision Victim

A 37-year-old woman is on a volume-cycled mechanical ventilator on a day when the barometric pressure is 745 mm Hg. The patient is receiving an FI_{O_2} of 0.50. The following clinical data are obtained:

Hb:	11 g/dL
(Pa_{O_2})	60 mm Hg (Sa_{O_2} = 90%)
$P\bar{v}_{O_2}$	35 mm Hg ($S\bar{v}_{O_2}$ = 65%)
Pa_{CO_2}	38 mm Hg
Cardiac output:	6 L/min

Based on this information, calculate the patient's

A. Total oxygen delivery ______

B. Arterial-venous oxygen content difference ______

C. Intrapulmonary shunting ______

D. Oxygen consumption ______

E. Oxygen extraction ratio ______

Clinical Application Questions

Case 1

1. As a result of the gunshot wound to the chest, the patient lost a large amount of blood. Because of the excessive blood loss, the patient was

______

2. As a result of the excessive blood loss, the patient's Pa_{O_2} of 503 mm Hg and Sa_{O_2} of 98 percent were very misleading. Which oxygen transport studies verified this fact?

______

3. In the first oxygen transport study, the patient's D_{O_2} was only 316 mL. Her $\dot{V}_{O_2}$ was 214 mL. What was her O_2ER?

______

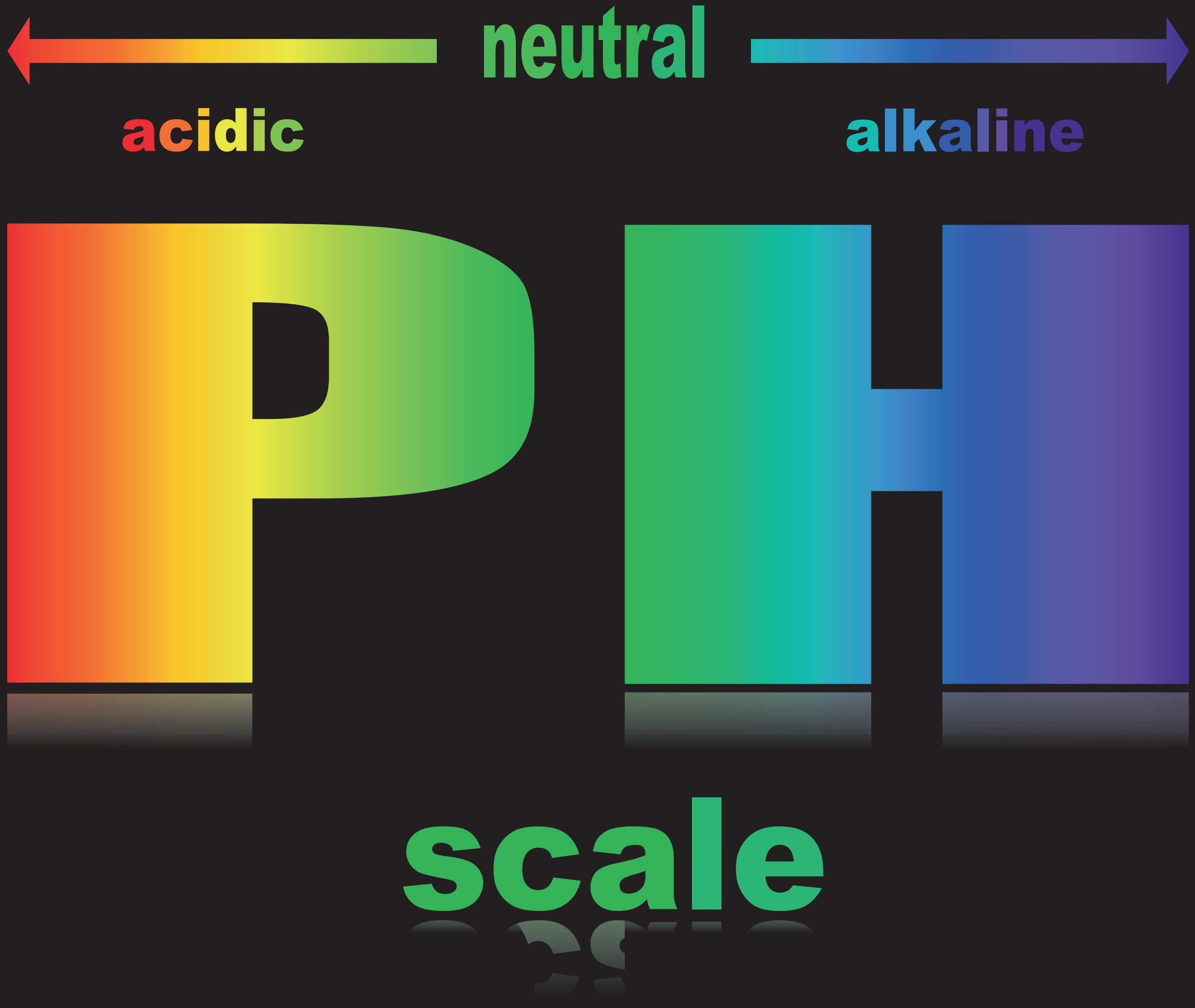
Case 2

1. As a result of the asthmatic episode, the patient's PA_{O_2} (decreased ______, increased ______), and the alveolar carbon dioxide (PA_{CO_2}) (decreased ______, increased ______).

2. As the preceding condition worsened, the patient's intrapulmonary shunting ($\dot{Q}s/\dot{Q}_T$) (decreased ______, increased ______), the oxygen extraction ratio (O_2ER) (decreased ______, increased ______), and the total oxygen delivery (D_{O_2}) (decreased ______, increased ______).

3. The patient's condition was compromised by the presence of a decreased pH (7.25) and an increased (Pa_{CO_2}) (72 mm Hg), which caused the oxyhemoglobin dissociation curve to shift to the ______.

4. Because of the condition described in question 3, the patient's hemoglobin saturation was (higher ______, lower ______) than expected for a particular Pa_{O_2} level.


neutral
acidic
alkaline
PH
scale

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CHAPTER 7

Acid–Base Balance and Regulation

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the acid–base balance and regulation of the body.
2. Identify the following acid–base disturbances on the $P_{CO_2}/HCO_3^-/pH$ nomogram: acute ventilatory failure with respiratory acidosis, acute ventilatory failure with partial renal compensation, and chronic ventilatory failure with complete renal compensation.
3. Identify common causes of acute ventilatory failure.
4. Identify the following acid–base disturbances on the $P_{CO_2}/HCO_3^-/pH$ nomogram: acute alveolar hyperventilation (respiratory alkalosis), acute alveolar hyperventilation (with partial renal compensation), and chronic alveolar hyperventilation (with complete renal compensation).
5. Identify common causes of acute alveolar hyperventilation.
6. Identify the following acid–base disturbances on the $P_{CO_2}/HCO_3^-/pH$ nomogram: metabolic acidosis, including the anion gap; metabolic acidosis with partial respiratory compensation; metabolic acidosis with complete respiratory compensation; and combined metabolic and respiratory acidosis.
7. Identify common causes of metabolic acidosis.
8. Identify the following acid–base disturbances on the $P_{CO_2}/HCO_3^-/pH$ nomogram: metabolic alkalosis, metabolic alkalosis with partial respiratory compensation, metabolic alkalosis with complete respiratory compensation, and combined metabolic and respiratory alkalosis.
9. Identify common causes of metabolic alkalosis.
10. Describe base excess/deficit.

Introduction

Nearly all biochemical reactions in the body are influenced by the acid–base balance of their fluid environment. When the pH is either too high or too low, essentially nothing in the body functions properly. Under normal conditions, the blood pH remains within a very narrow range. The normal arterial pH range is 7.35 to 7.45. The normal venous pH range is 7.30 to 7.40. When the pH of the arterial blood is greater than 7.45, **alkalosis** or **alkalemia** is said to exist; the blood has an excess amount of bicarbonate ions (HCO_3^-). When the pH falls below 7.35, **acidosis** or **acidemia** is said to be present; the blood has an excess amount of hydrogen ions (H^+).

Most H^+ ions in the body originate from (1) the breakdown of phosphorous-containing proteins (phosphoric acid), (2) the anaerobic metabolism of glucose (lactic acid), (3) the metabolism of body fats (fatty and ketone acids), and (4) the transport of CO_2 in the blood as HCO_3^- liberates H^+ ions. Under normal conditions, both the H^+ and HCO_3^- ion concentrations in the blood are regulated by the following three major systems: the *chemical buffer system,* the *respiratory system,* and the *renal system.*

The **chemical buffer system** responds within a fraction of a second to resist pH changes and is called the *first line of defense*. This system is composed of (1) the *carbonic acid–bicarbonate buffer system,* (2) the *phosphate buffer system,* and (3) the *protein buffer system*. The chemical buffer system inactivates H^+ ions and liberates HCO_3^- ions in response to acidosis or generates more H^+ ions and decreases the concentration of HCO_3^- ions in response to alkalosis.

The **respiratory system** acts within 1 to 3 minutes by increasing or decreasing the breathing depth and rate to offset acidosis or alkalosis, respectively. For example, in response to metabolic acidosis, the respiratory system causes the depth and rate of breathing to increase, causing the body's CO_2 to decrease and the pH to increase. In response to metabolic alkalosis, the respiratory system causes the depth and rate of breathing to decrease, causing the body's CO_2 to increase and the pH to decrease.

The **renal system** is the body's most effective acid–base balance monitor and regulator. The renal system requires a day or more to correct abnormal pH concentrations. When the extracellular fluids become acidic, the renal system retains HCO_3^- and excretes H^+ ions into the urine, causing the blood pH to increase. On the other hand, when the extracellular fluids become alkaline, the renal system retains H^+ and excretes basic substances (primarily HCO_3^-) into the urine, causing the blood pH to decrease.

To fully appreciate acid–base balance, and how it is normally regulated, a fundamental understanding of acids and bases, and their influences on pH, is essential.

Basic Principles of Acid–Base Reactions and pH

Acids and Bases

Similar to salts, acids and bases are electrolytes. Thus, both acids and bases can ionize and dissociate in water and conduct an electrical current.

Acids

Acids are sour tasting, can react with many metals, and can "burn" a hole through clothing. With regard to acid–base physiology, however, an acid is a substance that releases **hydrogen ions** [H^+] in measurable amounts. Because a hydrogen ion is only a hydrogen nucleus proton, acids are defined as **proton donors**. Thus, when acids dissolve in a water solution, they release hydrogen ions (protons) and anions.

The acidity of a solution is directly related to the concentration of protons. In other words, the acidity of a solution reflects only the free hydrogen ions, not those bound to anions. For example, *hydrochloric acid* (HCl), the acid found in the stomach that works to aid digestion, dissociates into a proton and a chloride ion:

$$HCl \longrightarrow \underset{\text{proton}}{H^+}\ \underset{\text{anion}}{Cl^-}$$

Other acids in the body include acetic acid ($HC_2H_3O_2$), often abbreviated as [HAc], and carbonic acid (H_2CO_3). The molecular formula for common acids is easy to identify because it begins with the hydrogen ion.

Strong and Weak Acids. First, it is important to remember that the acidity of a solution reflects only the free hydrogen ions—not the hydrogen ions still combined with anions. Thus, **strong acids**, which dissociate completely (i.e., they liberate all the H^+) and irreversibly in water, dramatically change the pH of the solution. For example, if 100 hydrochloric (HCl) acid molecules were placed in 1 mL of water, the hydrochloric acid would dissociate into 100 H^+ and 100 Cl^- ions. There would be no undissociated hydrochloric acid molecules in the solution.

Weak acids, on the other hand, do not dissociate completely in a solution and, therefore, have a much smaller effect on pH. However, even though weak acids have a relatively small effect on changing pH levels, they have a very important role in resisting sudden pH changes. Examples of weak acids are carbonic acid (H_2CO_3) and acetic acid ($HC_2H_3O_2$). If 100 acetic acid molecules were placed in 1 mL of water, only one acidic acid molecule would likely be ionized at any given moment as shown in the following reaction:

$$100\ HC_2H_3O_2 \rightarrow 99\ HC_2H_3O_2 + \underset{\text{(hydrogen ions)}}{1H^+} + \underset{\text{(acetate ions)}}{1\ C_2H_3O_2}$$

Because undissociated acids do not alter the pH, the acidic solution will not be as acidic as the HCl solution discussed earlier. Because the dissociation of weak acids is predictable, and because the molecules of intact acids are in constant dynamic equilibrium with the dissociated ions, the dissociation of acetic acid can be written as follows:

$$HC_2H_3O_2 \leftrightarrows H^+ + C_2H_3O_2^-$$

Using this equation, it can be seen that when H^+ (released by a strong acid) is added to the acetic acid solution, the equilibrium moves to the left as some of the additional H^+ bonds with $C_2H_3O_2^-$ to form $HC_2H_3O_2$. On the other hand, when a strong base is added to the solution (adding additional OH^- and causing the pH to increase), the equilibrium shifts to the right. This occurs because the additional OH^- consumes the H^+. This causes more $HC_2H_3O_2$ molecules to dissociate and replenish the H^+. Weak acids play a very important role in the chemical buffer systems of the human body.

Bases

Bases are **proton acceptors**. Bases taste bitter and feel slippery. With regard to acid–base physiology, a base is a substance that takes up hydrogen ions [H^+] in measurable amounts. Common inorganic bases include the hydroxides, for example, magnesium hydroxide (milk of magnesia) and sodium hydroxide (lye). Similar to acids, when dissolved in water, hydroxides dissociate into **hydroxide ions** (OH^-) and cations. For example, ionization of sodium hydroxide (NaOH) results in a hydroxide ion and a sodium ion. The liberated hydroxide ion then bonds, or accepts, a proton present in the solution. This reaction produces water and, at the same time, decreases the acidity [H^+ concentration] of the solution:

$$NaOH \rightarrow \underset{\text{cation}}{Na^+} + \underset{\text{hydroxide ion}}{OH^-}$$

and then

$$OH^- + H^+ \rightarrow \underset{\text{water}}{H_2O}$$

The **bicarbonate ion (HCO_3^-)** is an important base in the body and is especially abundant in the blood. **Ammonia** (NH_3), a natural waste product of protein breakdown, is also a base. Ammonia has a pair of unshared electrons that strongly attract protons. When accepting a proton, ammonia becomes an ammonium ion:

$$NH_3 + H^+ \rightarrow \underset{\text{ammonium ion}}{NH_4^+}$$

Strong and Weak Bases. With regard to strong and weak bases, it is important to remember that bases are proton acceptors. **Strong bases** (e.g., hydroxides) dissociate easily in water and quickly tie up H^+. In contrast, **weak bases** (e.g., sodium bicarbonate or baking soda) dissociate incompletely and reversibly and are slower to accept protons. Because sodium bicarbonate accepts a relatively small amount of protons, its released bicarbonate ion is described as a weak base.

pH: Acid–Base Concentration

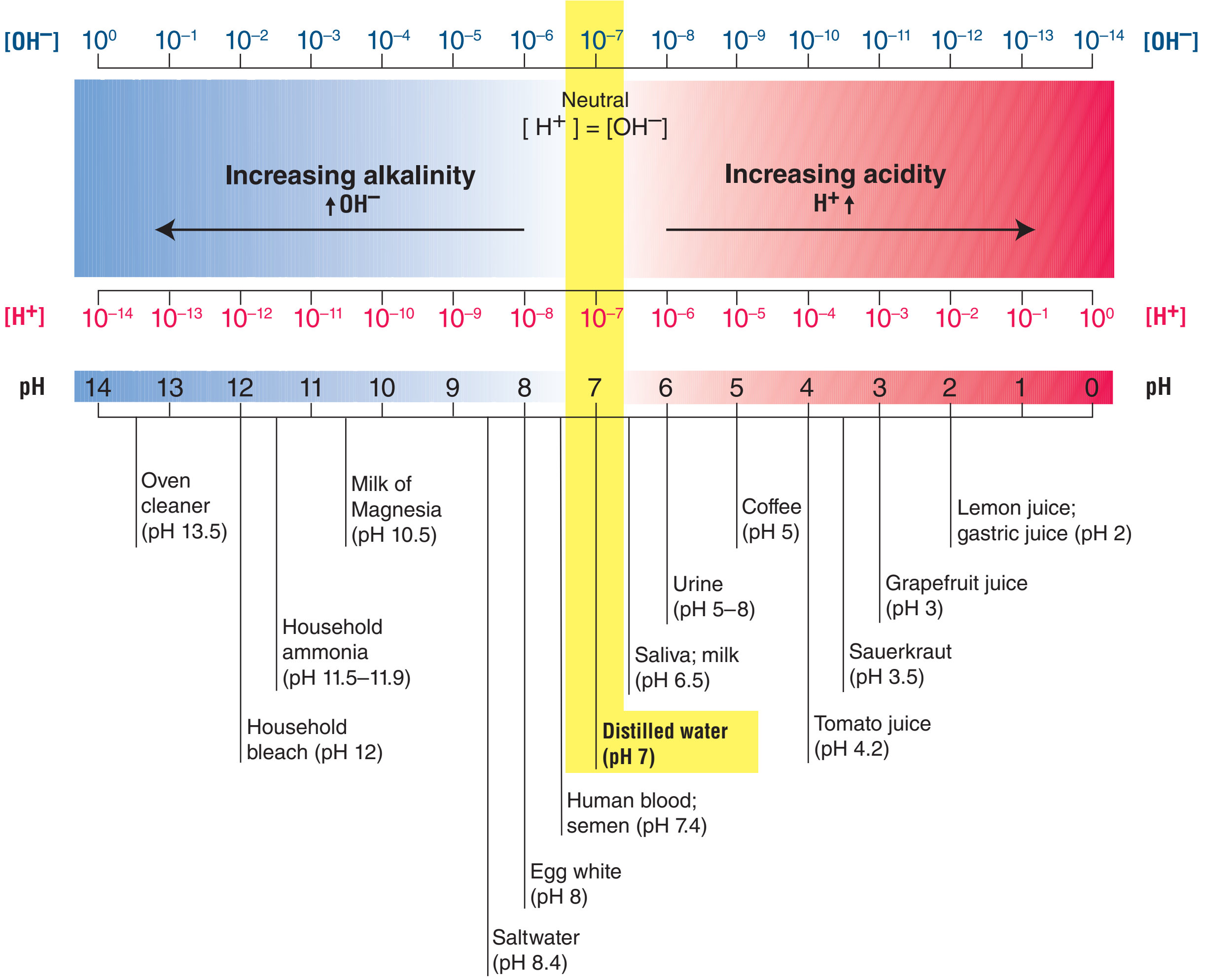
As the concentration of hydrogen ions in a solution increases, the solution becomes more acidic. On the other hand, as the level of hydroxide ions increases, the solution becomes more basic, or alkaline. Clinically, the concentration of hydrogen ions in the body is measured in units called *pH units*. The pH scale runs from 0 to 14 and is logarithmic, which means each successive unit change in pH represents a tenfold change in hydrogen ion concentration. The **pH** of a solution, therefore, *is defined as the negative logarithm, to the base 10, off the hydrogen ion concentration* $[H^+]$ *in moles per liter, or* $-\log H^+$:

$$pH = -\log_{10} [H^+]$$

When the pH is 7 ($H^+ = 10^{-7}$ mol/L), the number of hydrogen ions precisely equals the number of hydroxide ions (OH^-), and the solution is neutral—that is, neither acidic nor basic. Pure water has a neutral pH of 7, or 10^{-7} mol/L (0.0000001 mol/L) of hydrogen ions. A solution with a pH below 7 is acidic—that is, there are more hydrogen ions than hydroxide ions. For example, a solution with a pH of 6 has 10 times more hydrogen ions than a solution with a pH of 7.

A solution with a pH greater than 7 is alkaline—that is, the hydroxide ions outnumber the hydrogen ions. For example, a solution with a pH of 8 has 10 times more hydroxyl ions than a solution with a pH of 7. Thus, as the hydrogen ion concentration increases, the hydroxide ion concentration falls, and vice versa. Figure 7–1 provides the approximate pH values of several human fluids and common household substances.

FIGURE 7-1 The pH values of representative substances. The pH scale represents the number of hydrogen ions in a substance. The concentration of hydrogen ions (H^+) and the corresponding hydroxyl concentration (OH^-) for each representative substance are also provided. Note that when the pH is 7.0, the amounts of H^+ and OH^- are equal and the solution is neutral.


[OH⁻]
10⁰ 10⁻¹ 10⁻² 10⁻³ 10⁻⁴ 10⁻⁵ 10⁻⁶ 10⁻⁷ 10⁻⁸ 10⁻⁹ 10⁻¹⁰ 10⁻¹¹ 10⁻¹² 10⁻¹³ 10⁻¹⁴
[OH⁻]
Neutral
[H⁺] = [OH⁻]
Increasing alkalinity
↑OH⁻
Increasing acidity
H⁺↑
[H⁺]
10⁻¹⁴ 10⁻¹³ 10⁻¹² 10⁻¹¹ 10⁻¹⁰ 10⁻⁹ 10⁻⁸ 10⁻⁷ 10⁻⁶ 10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 10⁰
[H⁺]
pH
14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
pH
Oven cleaner (pH 13.5)
Milk of Magnesia (pH 10.5)
Coffee (pH 5)
Lemon juice; gastric juice (pH 2)
Urine (pH 5–8)
Grapefruit juice (pH 3)
Household ammonia (pH 11.5–11.9)
Saliva; milk (pH 6.5)
Sauerkraut (pH 3.5)
Household bleach (pH 12)
Distilled water (pH 7)
Tomato juice (pH 4.2)
Human blood; semen (pH 7.4)
Egg white (pH 8)
Saltwater (pH 8.4)

Chemical Buffer Systems and Acid–Base Balance

Chemical buffers resist pH changes and are the body's first line of defense. The ability of an acid–base mixture to resist sudden changes in pH is called its **buffer action**. The tissue cells and vital organs of the body are extremely sensitive to even the slightest change in the pH environment. In high concentrations, both acids and bases can be extremely damaging to living cells—essentially every biological process within the body is disrupted.

Buffers work against sudden and large changes in the pH of body fluids by releasing hydrogen ions (acting as acids) when the pH increases and binding hydrogen ions (acting as bases) when the pH decreases. The three major chemical buffer systems in the body are the *carbonic acid–bicarbonate buffer system,* the *phosphate buffer system,* and the *protein buffer system.*

Carbonic Acid–Bicarbonate Buffer System and Acid–Base Balance

The **carbonic acid–bicarbonate buffer system** plays an extremely important role in maintaining pH homeostasis of the blood. Carbonic acid (H_2CO_3) dissociates reversibly and releases bicarbonate ions (HCO_3^-) and protons (H^+) as follows:

$$\underset{\substack{\text{H}^+\text{ donor}\\\text{(weak acid)}}}{H_2CO_3} \quad \underset{\text{Response to a decrease in pH}}{\overset{\text{Response to an increase in pH}}{\rightleftharpoons}} \quad \underset{\substack{\text{H}^+\text{ acceptor}\\\text{(weak proton)}}}{HCO_3^-} + \underset{\text{proton}}{H^+}$$

Under normal conditions, the ratio between HCO_3^- and H_2CO_3 in the blood is 20:1 (refer to Figure 6–20). The chemical equilibrium between carbonic acid (weak acid) and bicarbonate ion (weak base) works to resist sudden changes in blood pH. For example, when the blood pH increases (i.e., becomes more alkaline from the addition of a strong base), the equilibrium shifts to the right. A right shift forces more carbonic acid to dissociate, which in turn causes the pH to decrease.

In contrast, when the blood pH decreases (i.e., becomes more acidic from the addition of a strong acid), the equilibrium moves to the left. A left shift forces more bicarbonate to bind with protons. In short, the carbonic acid–bicarbonate buffer system converts strong bases to a weak base (bicarbonate ion) and strong acids to a weak acid (carbonic acid). As a result, blood pH changes are much less than they would be if this buffering system did not exist.

The Henderson–Hasselbalch Equation

The **Henderson–Hasselbalch (H-H) equation** mathematically illustrates how the pH of a solution is influenced by the HCO_3^- to H_2CO_3 ratio (base to acid ratio). The H-H equation is written as follows:

$$pH = pK + \log \frac{[HCO_3^-]\ \text{(base)}}{[H_2CO_3]\ \text{(acid)}}$$

The pK is derived from the dissociation constant of the acid portion of the buffer combination. The pK is 6:1 and, under normal conditions, the HCO_3^- to H_2CO_3 ratio is 20:1.

Clinically, the dissolved CO_2 ($P_{CO_2} \times 0.03$) can be used for the denominator of the H-H equation instead of the H_2CO_3. This is possible because the dissolved carbon dioxide is in equilibrium with, and directly proportional to, the blood $[H_2CO_3]$. This is handy because the patient's value can easily be obtained from an arterial blood gas. Thus, the H-H equation can be written as follows:

$$pH = pK + \log \frac{[HCO_3^-]}{[P_{CO_2} \times 0.03]}$$

H-H Equation Applied during Normal Conditions. When the HCO_3^- is 24 mEq/L, and the Pa_{CO_2} is 40 mm Hg, the base to acid ratio is 20:1 and the pH is 7.4 (normal). The H-H equation confirms the 20:1 ratio and pH of 7.4 as follows:

$$\begin{aligned}
pH &= pK + \log\frac{[HCO_3^-]}{[P_{CO_2} \times 0.03]}\\
&= 6.1 + \log\frac{24\ mEq/L}{(40 \times 0.03)}\\
&= 6.1 + \log\frac{24\ mEq/L}{(1.2\ mEq/L)}\\
&= 6.1 + \log\frac{20}{1} \qquad (20{:}1\ \text{ratio})\\
&= 6.1 + 1.3\\
&= 7.4
\end{aligned}$$

H-H Equation Applied during Abnormal Conditions. When the HCO_3^- is 29 mEq/L, and the Pa_{CO_2} is 80 mm Hg, the base to acid ratio decreases to 12:1 and the pH is 7.18 (acidic). The H-H equation confirms the 12:1 ratio and the pH of 7.18 as follows:

$$\begin{aligned}
pH &= pK + \log\frac{[HCO_3^-]}{[P_{CO_2} \times 0.03]}\\
&= 6.1 + \log\frac{29\ mEq/L}{(80 \times 0.03)}\\
&= 6.1 + \log\frac{29\ mEq/L}{(2.4\ mEq/L)}\\
&= 6.1 + \log\frac{12}{1} \qquad (12{:}1\ \text{ratio})\\
&= 6.1 + 1.08\\
&= 7.18
\end{aligned}$$

In contrast, when the HCO_3^- is 20 mEq/L, and the Pa_{CO_2} is 20 mm Hg, the base to acid ratio increases to 33:1 and the pH is 7.62 (alkalotic). The H-H equation confirms the 33:1 ratio and the pH of 7.62 as follows:

$$\begin{aligned}
pH &= pK + \log\frac{[HCO_3^-]}{[P_{CO_2} \times 0.03]}\\
&= 6.1 + \log\frac{20\ mEq/L}{(20 \times 0.03)}\\
&= 6.1 + \log\frac{20\ mEq/L}{(0.6\ mEq/L)}\\
&= 6.1 + \log\frac{33}{1} \qquad (33{:}1\ \text{ratio})\\
&= 6.1 + 1.52\\
&= 7.62
\end{aligned}$$

Clinical Application of the H-H Equation

Clinically, the H-H equation can be used to calculate the pH, $[HCO_3^-]$, or Pa_{CO_2} when any two of these three variables are known. $[HCO_3^-]$ is solved as follows:

$$[HCO_3^-] = \text{antilog}(7.40 - 6.1) \times (P_{CO_2} \times 0.03)$$

P_{CO_2} is determined as follows:

$$P_{CO_2} = \frac{[HCO_3^-]}{(\text{antilog }[pH - 6.1] \times 0.03)}$$

The H-H equation may be helpful in cross-checking the validity of the blood gas reports when the pH, P_{CO_2}, and $[HCO_3^-]$ values appear out of line. It may also be useful in estimating what changes to expect when any one of the H-H equation components is altered. For example, consider the case example that follows.

Case. A mechanically ventilated patient has a pH of 7.54, a Pa_{CO_2} of 26 mm Hg, and a HCO_3^- of 22 mEq/L. The physician asks the respiratory therapist to adjust the patient's Pa_{CO_2} to a level that will decrease the pH to 7.45. Using the H-H equation, the Pa_{CO_2} change needed to decrease the pH to 7.45 can be estimated as follows:

$$\begin{aligned} P_{CO_2} &= \frac{[HCO_3^-]}{(\text{antilog }[pH - 6.1] \times 0.03)} \\ &= \frac{22}{\text{antilog }(7.45 - 6.1) \times 0.03} \\ &= \frac{22}{\text{antilog }(1.35) \times 0.03} \\ &= \frac{22}{22.38 \times 0.03} \\ &= \frac{22}{0.67} \\ &= 32.8 \text{ or } 33 \text{ mm Hg} \end{aligned}$$

Thus, increasing the Pa_{CO_2} to about 33 mm Hg should move the patient's pH level close to 7.45. In this case, the respiratory therapist would begin by either decreasing the tidal volume, or the respiratory rate, on the mechanical ventilator. After the ventilator changes are made, another arterial blood gas should be obtained in about 20 minutes. The pH and Pa_{CO_2} should be reevaluated and followed by appropriate ventilator adjustments if necessary.

Phosphate Buffer System and Acid–Base Balance

The function of the **phosphate buffer system** is almost identical to that of the carbonic acid–bicarbonate buffer system. The primary components of the phosphate buffer system are the sodium salts of dihydrogen phosphate ($H_2PO_4^-$) and monohydrogen phosphate (HPO_4^-). NaH_2PO_4 is a weak acid. Na_2HPO_4, which has one less hydrogen atom, is a weak base. When H^+ ions are released by a strong acid, the phosphate buffer system works to inactivate the acidic effects of the H^+ as follows:

$$\underset{\text{strong acid}}{HCl} + \underset{\text{weak base}}{Na_2HPO_4} \rightarrow \underset{\text{weak acid}}{NaH_2PO_4} + \underset{\text{salt}}{NaCl}$$

On the other hand, strong bases are converted to weak bases as follows:

$$\underset{\text{strong base}}{NaOH} + \underset{\text{weak acid}}{NaH_2PO_4} \rightarrow \underset{\text{weak base}}{Na_2HPO_4} + \underset{\text{water}}{H_2O}$$

Because the phosphate buffer system is only about one-sixth as effective as that of the carbonic acid–bicarbonate buffer system in the extracellular fluid, it is not an effective buffer for blood plasma. However, it is an effective buffer system in urine and in intracellular fluid where the phosphate levels are typically greater.

Protein Buffer System and Acid–Base Balance

The body's most abundant and influential supply of buffers is the **protein buffer system**. Its buffers are found in the proteins in the plasma and cells. In fact, about 75 percent of the buffering power of body fluids is found in the intracellular proteins. Proteins are polymers of amino acids. Some of the amino acids have exposed groups of atoms known as organic acid (carboxyl) groups (—COOH), which dissociate and liberate H^+ in response to a rising pH:

$$R^1\text{—COOH} \rightarrow \text{—COO}^- + H^+$$

In contrast, other amino acids consist of exposed groups that can function as bases and accept H^+. For example, an exposed —NH_2 group can bond with hydrogen ions to form $\text{—NH}_3{}^+$:

$$R\text{—NH}_2 + H^+ \rightarrow R\text{—NH}_3{}^+$$

Because this reaction ties up free hydrogen ions, it prevents the solution from becoming too acidic. In addition, a single protein molecule can function as either an acid or a base relative to its pH environment. Protein molecules that have a reversible ability are called **amphoteric molecules**.

The hemoglobin in red blood cells is a good example of a protein that works as an intracellular buffer. As discussed earlier, CO_2 released at the tissue cells quickly forms H_2CO_3, and then dissociates into H^+ and $HCO_3{}^-$ ions (refer to Figure 6–20). At the same time, the hemoglobin is unloading oxygen at the tissue sites and becoming *reduced hemoglobin*. Because reduced hemoglobin carries a negative charge, the free H^+ ions quickly bond to the hemoglobin anions. This action reduces the acidic effects of the H^+ on the pH. In essence, the H_2CO_3, which is a weak acid, is buffered by an even weaker acid—the hemoglobin protein.

The Respiratory System and Acid–Base Balance

Although the respiratory system does not respond as fast as the chemical buffer systems, it has up to two times the buffering power of all of the chemical buffer systems combined. As discussed earlier, the respiratory system eliminates CO_2 from the body while at the same time replenishing it with O_2. The CO_2 produced at the tissue cells enters the red blood cells and is converted to $HCO_3{}^-$ ions as follows:

$$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3{}^-$$

The first set of double arrows illustrates a reversible equilibrium between the dissolved carbon dioxide and the water on the left and carbonic acid on the right. The second set of arrows shows a reversible equilibrium between carbonic acid on the left and hydrogen and bicarbonate ions on the right. Because of this relationship, an increase in any of these chemicals causes a shift in the opposite direction. Note also that the right side of this equation is the same as that for the carbonic acid–bicarbonate buffer system.

Under normal conditions, the volume of CO_2 eliminated at the lung is equal to the amount of CO_2 produced at the tissues. When the CO_2 is unloaded at the lungs, the preceding equation flows to the left, and causes the H^+ generated from the carbonic acid to transform back to water (refer to Figure 6–21). Because of the protein buffer system (discussed earlier), the H^+ generated by the CO_2 transport system is not permitted to increase and, therefore, has little or no effect on blood pH.

However, under abnormal conditions, the respiratory system quickly responds by either increasing or decreasing the rate and depth of breathing to compensate for acidosis or alkalosis, respectively. For example, when the pH declines (e.g., metabolic acidosis caused by lactic acids), the respiratory system responds by increasing the breathing depth and rate. This action causes more CO_2 to be eliminated from the lungs and, therefore, pushes the preceding reaction to the left and reduces the H^+ concentration. This process works to

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[1] R represents the entire organic molecule, which is composed of many atoms.

return the acidic pH back to normal. On the other hand, when the pH rises (e.g., metabolic alkalosis caused by hypokalemia), the respiratory system responds by decreasing the breathing depth and rate. This action causes less CO_2 to be eliminated from the lungs and, thus, moves the preceding reaction to the right and increases the H^+ concentration. This works to pull the alkalotic pH back to normal.

Finally, note that when the respiratory system is impaired for any reason, a serious acid–base imbalance can develop. For example, severe head trauma can cause a dramatic increase in the depth and rate of breathing that is completely unrelated to the CO_2 concentration. When this happens, the volume of CO_2 expelled from the lungs will be greater than the amount of CO_2 produced at the tissue cells. In other words, **hyperventilation** is present. This condition causes the pH to increase and **respiratory alkalosis** is said to exist. In contrast, the ingestion of barbiturates can cause a dramatic decrease in the depth and rate of breathing. When this occurs, the volume of CO_2 eliminated from the lungs is less than the amount of CO_2 produced at the tissue cells. In this case, **hypoventilation** is present. This condition causes the pH to fall and **respiratory acidosis** is said to exist. The control of ventilation is presented in Chapter 9.

The Renal System and Acid–Base Balance

Even though the chemical buffer systems can inactivate excess acids and bases momentarily, they are unable to eliminate them from the body. Similarly, although the respiratory system can expel the volatile carbonic acid by eliminating CO_2, it cannot expel other acids generated by cellular metabolism. Only the *renal system* can rid the body of acids such as phosphoric acids, uric acids, lactic acids, and ketone acids (also called fixed acids).

In addition, only the renal system can regulate alkaline substances in the blood and restore chemical buffers that are used up in managing the H^+ levels in the extracellular fluids. (For example, some HCO_3^-, which helps to adjust H^+ concentrations, is lost from the body when CO_2 is expelled from the lungs.) Basically, when the extracellular fluids become acidic, the renal system retains HCO_3^- and excretes H^+ ions into the urine, causing the blood pH to increase. On the other hand, when the extracellular fluids become alkaline, the renal system retains H^+ and excretes basic substances (primarily HCO_3^-) into the urine, causing the blood pH to decrease.

The Role of the $P_{CO_2}/HCO_3^-/pH$ Relationship in Acid–Base Balance

Acid–Base Balance Disturbances

As shown earlier in this chapter, the normal bicarbonate (HCO_3^-) to carbonic acid (H_2CO_3) ratio in the blood plasma is 20:1. In other words, for every H_2CO_3 ion produced in blood plasma, 20 HCO_3^- ions must be formed to maintain a 20:1 ratio (normal pH). Or, for every H_2CO_3 ion loss in the blood plasma, 20 HCO_3^- ions must be eliminated to maintain a normal pH. In other words, the H_2CO_3 ion is 20 times more powerful than the HCO_3^- ion in changing the blood pH.

Under normal conditions, the 20:1 acid–base balance in the body is automatically regulated by the chemical buffer systems, the respiratory system, and the renal system. However, these normal acid–base regulating systems have their limits. The bottom line is this: The body's normal acid–base watchdog systems cannot adequately respond to sudden, large changes in H^+ and HCO_3^- concentrations—regardless of the cause.

For example, hypoventilation causes the partial pressure of the alveolar carbon dioxide ($P_{A_{CO_2}}$) to increase, which in turn causes the plasma P_{CO_2}, HCO_3^-, and H_2CO_3 to all increase. This chemical chain of events

FIGURE 7–2 Alveolar hypoventilation causes the $P_{A_{CO_2}}$ and the plasma P_{CO_2}, H_2CO_3, and HCO_3^- to increase. This action decreases the HCO_3^-/H_2CO_3 ratio, which in turn decreases the blood pH.

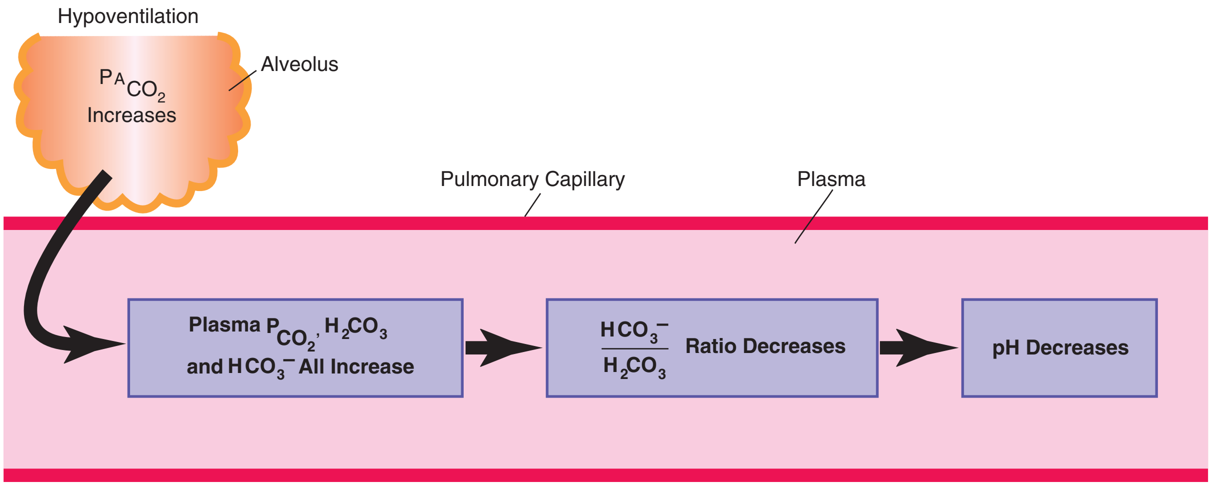
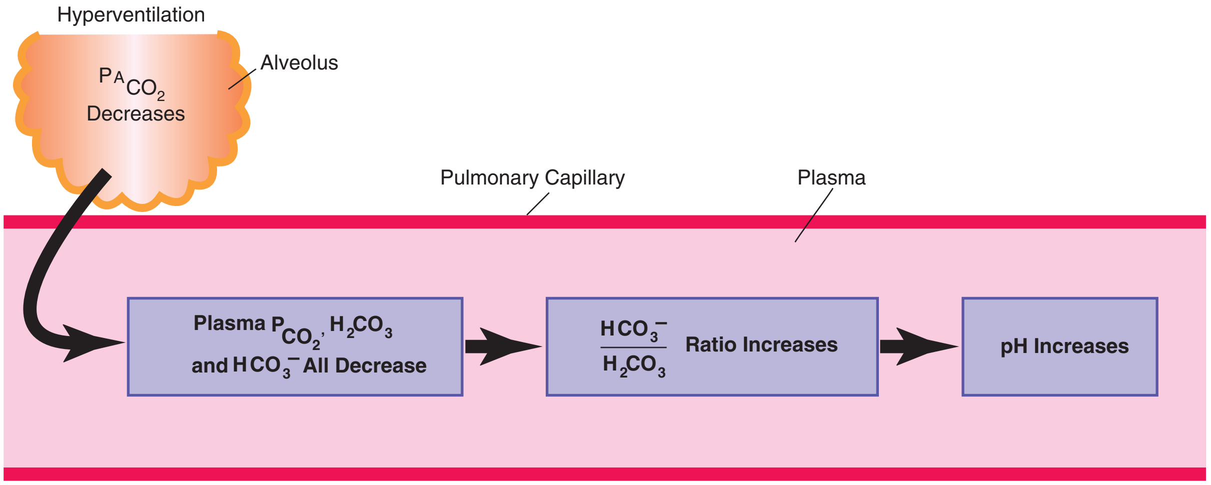

Hypoventilation
$P_{A_{CO_2}}$ Increases
Alveolus
Pulmonary Capillary
Plasma
Plasma P_{CO_2}, H_2CO_3 and HCO_3^- All Increase
$\frac{HCO_3^-}{H_2CO_3}$ Ratio Decreases
pH Decreases

FIGURE 7–3 Alveolar hyperventilation causes the $P_{A_{CO_2}}$ and the plasma P_{CO_2}, H_2CO_3, and HCO_3^- to decrease. This action increases the HCO_3^-/H_2CO_3 ratio, which in turn increases the blood pH.


Hyperventilation
$P_{A_{CO_2}}$ Decreases
Alveolus
Pulmonary Capillary
Plasma
Plasma P_{CO_2}, H_2CO_3 and HCO_3^- All Decrease
$\frac{HCO_3^-}{H_2CO_3}$ Ratio Increases
pH Increases

causes the HCO_3^- to H_2CO_3 ratio to decrease, and the pH to fall (Figure 7–2). Or, when the $P_{A_{CO_2}}$ decreases, as a result of alveolar hyperventilation, the plasma P_{CO_2}, HCO_3^-, and H_2CO_3 all decrease—which in turn causes the HCO_3^- to H_2CO_3 ratio to increase and the pH to rise (Figure 7–3).

The relationship between acute P_{CO_2} changes, and the resultant pH and HCO_3^- changes that occur, is graphically illustrated in the P_{CO_2}/HCO_3^-/pH nomogram (Figure 7–4). The P_{CO_2}/HCO_3^-/pH nomogram is an excellent clinical tool that can be used to identify a specific acid–base disturbance.[2] Table 7–1 provides an overview of the common acid–base balance disturbances that can be identified on the P_{CO_2}/HCO_3^-/pH nomogram. The following sections describe the common acid–base disturbances and how to identify them on the P_{CO_2}/HCO_3^-/pH nomogram.

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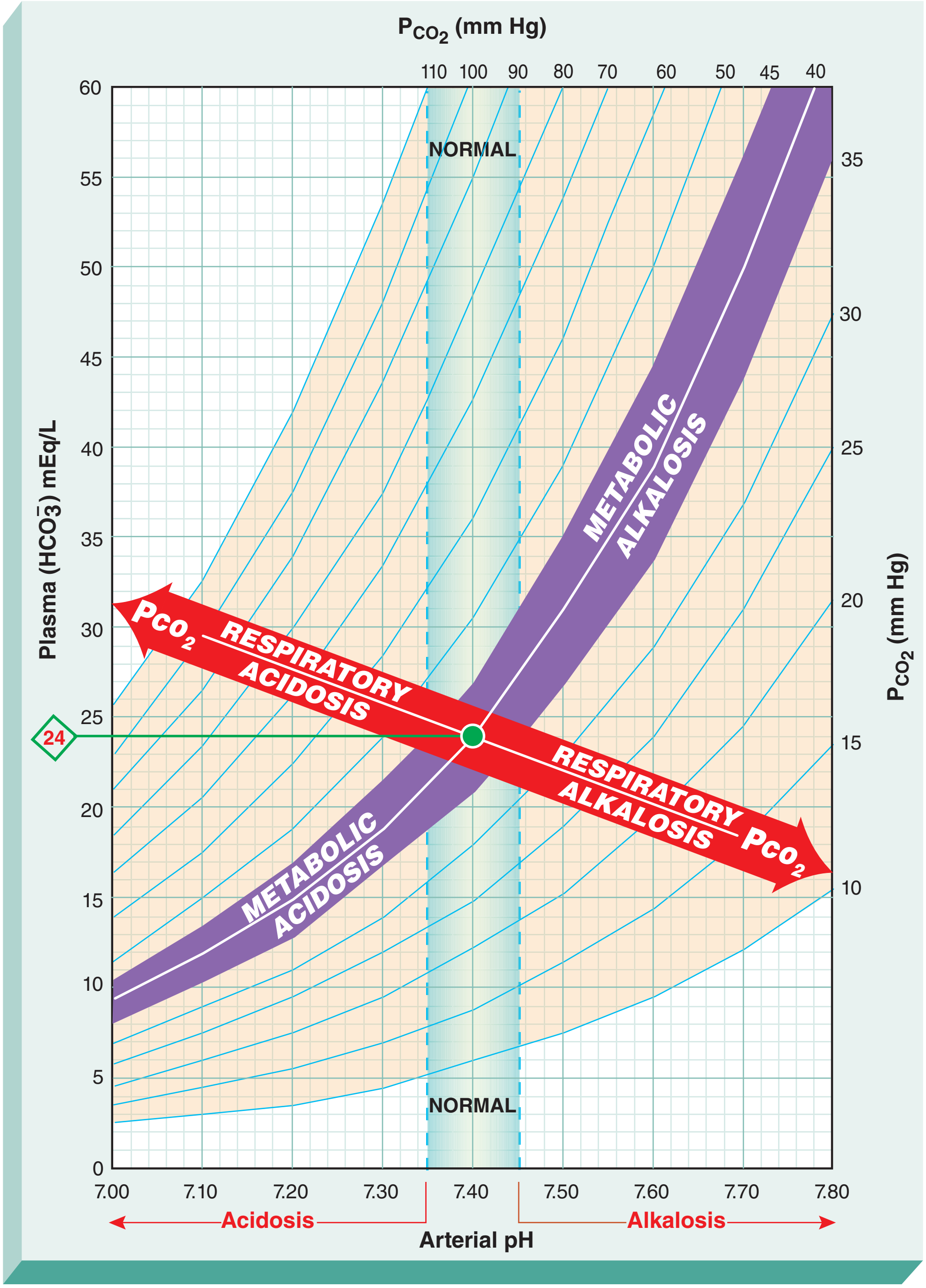
[2] See Appendix VI for a pocket-size P_{CO_2}/HCO_3^-/pH nomogram card that can be cut out, laminated, and used as a handy arterial blood gas reference tool in the clinical setting.

FIGURE 7-4 Nomogram of P_{CO_2}/HCO_3^-/pH relationship.



Respiratory Acid–Base Disturbances

Acute Ventilatory Failure (Respiratory Acidosis)

During **acute ventilatory failure** (e.g., acute hypoventilation caused by an overdose of narcotics or barbiturates), the PA_{CO_2} progressively increases. This action simultaneously causes an increase in the blood P_{CO_2}, H_2CO_3, and HCO_3^- levels. Because acute changes in H_2CO_3 levels are more significant than acute changes in

TABLE 7-1 Common Acid–Base Disturbance Classifications

- Respiratory acid–base disturbances
  - Acute ventilatory failure (respiratory acidosis)
  - Acute ventilatory failure with partial renal compensation
  - Chronic ventilatory failure with complete renal compensation
  - Acute alveolar hyperventilation (respiratory alkalosis)
  - Acute alveolar hyperventilation with partial renal compensation
  - Chronic alveolar hyperventilation with complete renal compensation
- Metabolic acid–base disturbances
  - Metabolic acidosis
  - Metabolic acidosis with partial respiratory compensation
  - Metabolic acidosis with complete respiratory compensation
  - Combined metabolic and respiratory acidosis
  - Metabolic alkalosis
  - Metabolic alkalosis with partial respiratory compensation
  - Metabolic alkalosis with complete respiratory compensation
  - Combined metabolic and respiratory alkalosis

Clinical Connection 7-1

P_{CO_2}/HCO_3^-/pH Relationship—Rule of Thumb

Clinically, the respiratory therapist will find the following general rules—based on the P_{CO_2}/HCO_3^-/pH nomogram presented in Figure 7–4—helpful when working to confirm the expected pH and HCO_3^- changes that occur in response to an "acute" increase or decrease in the P_{CO_2} level.

General Rules for the P_{CO_2} /HCO_3^-/pH Relationship

pH (Approximate)	P_{CO_2} (Approximate)	HCO_3^- (Approximate)
7.60	20	20
7.55	25	21
7.50	30	22
7.45	35	23
7.40	40	24
7.35	50	25
7.30	60	26
7.25	70	27
7.20	80	28

HCO_3^- levels, a decreased HCO_3^- to H_2CO_3 ratio develops (a ratio less than 20:1), which in turn causes the blood pH to decrease or become acidic (see Figure 7–2). The resultant pH and HCO_3^- changes, caused by a sudden increase in the P_{CO_2} level, can be easily identified by using the left side of the red-colored normal P_{CO_2} blood buffer bar located on the $P_{CO_2}/HCO_3^-/pH$ nomogram—titled "Respiratory Acidosis" in Figure 7–5.

FIGURE 7-5 Acute ventilatory failure is confirmed when the reported P_{CO_2}, pH, and HCO_3^- values all intersect within the red-colored "Respiratory Acidosis" bar. For example, when the reported P_{CO_2} is 80 mm Hg at a time when the pH is 7.18 and the HCO_3^- is 28 mEq/L, acute ventilatory failure is confirmed.

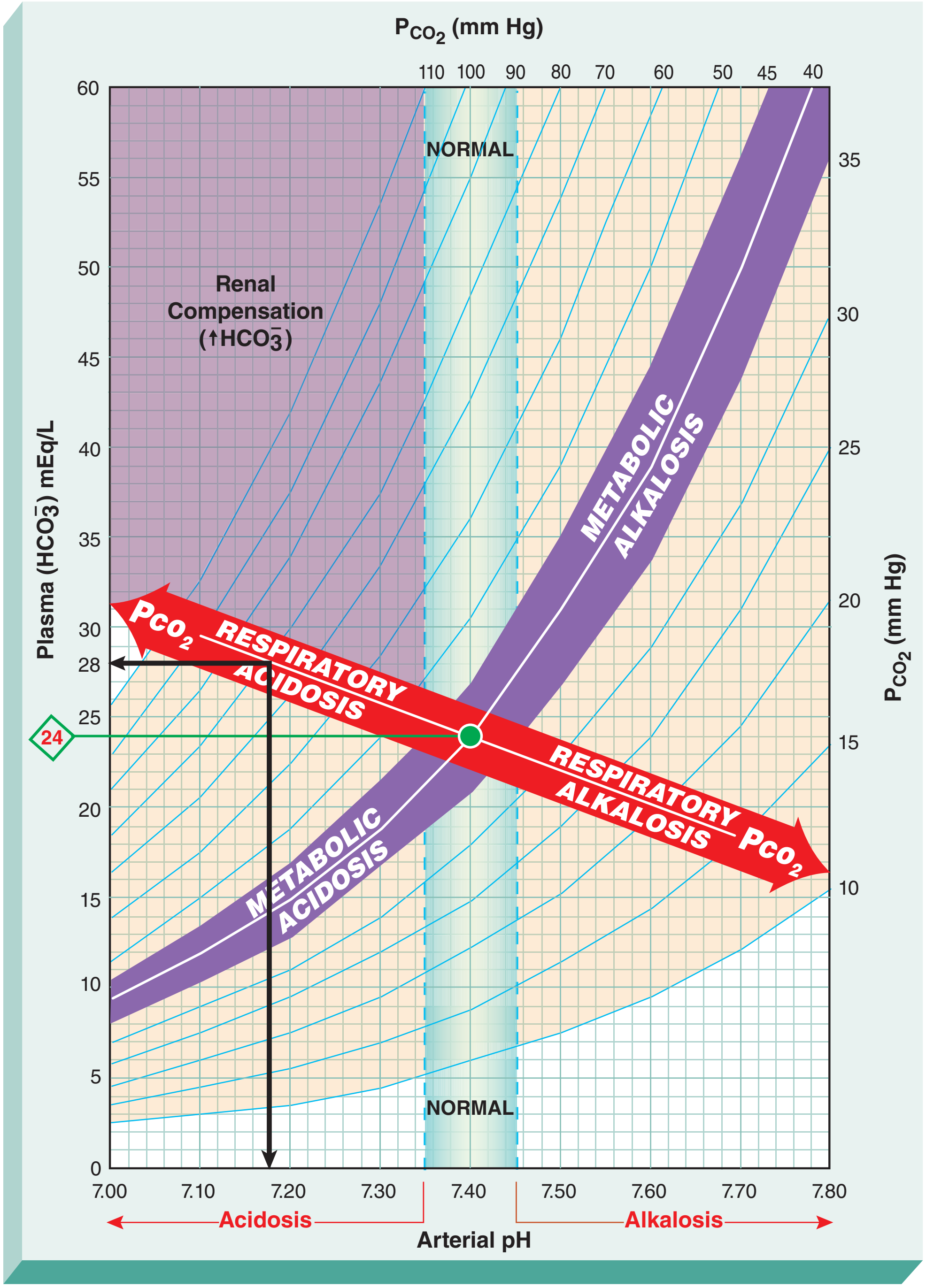


TABLE 7-2 Common Causes of Acute Ventilatory Failure

Chronic obstructive pulmonary disorders	Pulmonary disorders such as chronic emphysema and chronic bronchitis can lead to acute ventilatory failure.
Drug overdose	Drugs such as narcotics or barbiturates can depress ventilation.
General anesthesia	General anesthetics can cause ventilatory failure.
Head trauma	Severe trauma to the brain can cause acute ventilatory failure.
Neurologic disorders	Neurologic disorders such as Guillain–Barré syndrome and myasthenia gravis can lead to acute ventilatory failure.

Acute ventilatory failure is confirmed when the reported P_{CO_2}, pH, and HCO_3^- values all intersect within the red-colored "Respiratory Acidosis" bar. For example, when the reported P_{CO_2} is 80 mm Hg at a time when the pH is 7.18 and the HCO_3^- is 28 mEq/L, acute ventilatory failure is confirmed (see Figure 7–5). This is because all reported values (i.e., P_{CO_2}, HCO_3^-, and pH) intersect within the red-colored normal P_{CO_2} blood buffer bar, and the pH and HCO_3^- readings are precisely what is expected for an acute increase in the P_{CO_2} to 80 mm Hg (see Figure 7–5). Table 7–2 lists common causes of acute ventilatory failure.

Clinical Connection 7-2

Case Study—Acute Ventilatory Failure (Acute Respiratory Acidosis)

Acute ventilatory failure—also called *acute respiratory acidosis*—is a medical emergency! The patient requires immediate ventilatory assistance—for example, mouth-to-mouth ventilation, manual bag-and-mask ventilation, or mechanical ventilation. For example, consider the following case scenario.

CASE: A 20-year-old female presents in the emergency room as a result of a drug overdose from snorting heroin. She is unconscious, unresponsive, and appears cyanotic. Her pupils are dilated and fixed, and her breath sounds are diminished. Room air arterial blood gases (ABGs) and vital signs are as follows:

ABGs		Vital Signs	
pH:	7.22	Blood pressure:	145/95
Pa_{CO_2}:	78	Heart rate:	115
HCO_3^-:	28	Respiratory rate:	7 and shallow
Pa_{CO_2}:	38	Temperature:	98.6°F

The clinical interpretation of the preceding ABG is **acute ventilatory failure**—with **severe hypoxemia** (see Figure 7–5). Clinically, this ABG confirms the immediate need to provide this patient with mechanical ventilation. In fact, while the ventilator is being set up, the respiratory therapist should manually ventilate this patient with 100 percent oxygen. Once the patient is appropriately secured to a mechanical ventilator, a repeat ABG should be performed to make the appropriate ventilator adjustments to maintain the patient's ABG values in the normal range (i.e., pH—7.35–7.45, Pa_{CO_2}—35–45, HCO_3^-—24, Pa_{O_2}—80–100).

Acute ventilatory failure can be seen in any patient—young or old. It is not associated with a particular ventilatory pattern—for example, apnea, hyperpnea, or tachypnea. The bottom line is that acute ventilatory failure can develop in any condition that does not provide adequate alveolar ventilation—when an increased Pa_{CO_2} level is

Clinical Connection 7-2, Continued

accompanied with a decreased pH (acidemia), acute ventilatory failure is said to be present. In this case, the patient's ability to adequately ventilate her lungs was seriously compromised by an overdose of heroin. The respiratory therapist commonly provides care for patients who are in acute ventilatory failure. Other causes of acute ventilatory failure include COPD, general anesthesia, head trauma, and neurologic disorders (e.g., Guillain–Barré syndrome and myasthenia gravis).

Renal Compensation

In the patient who hypoventilates for a long period of time (e.g., because of chronic obstructive pulmonary disease), the kidneys will work to correct the decreased pH by retaining HCO_3^- in the blood. The presence of renal compensation is verified when the reported P_{CO_2}, HCO_3^-, and pH values all intersect in the purple-colored area shown in the upper left-hand corner of the $P_{CO_2}/HCO_3^-/pH$ nomogram of Figure 7–6.

Acute ventilatory failure with partial renal compensation (also called partially compensated respiratory acidosis) is present when the reported pH and HCO_3^- both are above the normal red-colored P_{CO_2} blood buffer bar (in the purple-colored area), but the pH is still less than normal. For example, when the P_{CO_2} is 80 mm Hg at a time when the pH is 7.30 and the HCO_3^- is 37 mEq/L, ventilatory failure with partial renal compensation is confirmed (see Figure 7–6).

Chronic ventilatory failure with complete renal compensation (also called compensated respiratory acidosis) is present when the HCO_3^- increases enough to cause the acidic pH to move back into the normal range (7.35 or higher), which, in this case, would be above 42 mEq/L (see Figure 7–6).

Acute Alveolar Hyperventilation (Respiratory Alkalosis)

During acute alveolar hyperventilation (e.g., hyperventilation due to pain and/or anxiety), the $P_{A_{CO_2}}$ will decrease and allow more CO_2 molecules to leave the pulmonary blood. This action simultaneously causes a decrease in the blood P_{CO_2}, H_2CO_3, and HCO_3^- levels. Because acute changes in H_2CO_3 levels are more significant than acute changes in HCO_3^- levels, an increased HCO_3^- to H_2CO_3 ratio develops (a ratio greater than 20:1), which in turn causes the blood pH to increase or become more alkaline (see Figure 7–3). The resultant pH and HCO_3^- changes caused by an acute decrease in the P_{CO_2} level can be easily identified by using the right side of the red-colored normal blood buffer bar located on the $P_{CO_2}/HCO_3^-/pH$ nomogram titled "Respiratory Alkalosis" (Figure 7–7).

Acute alveolar hyperventilation is confirmed when the reported P_{CO_2}, pH, and HCO_3^- values all intersect within the red-colored "Respiratory Alkalosis" bar. For example, when the reported P_{CO_2} is 25 mm Hg, at a time when the pH is 7.55 and the HCO_3^- is 21 mEq/L, acute alveolar hyperventilation is confirmed (see Figure 7–7). This is because all the reported values (i.e., P_{CO_2}, HCO_3^-, and pH) intersect within the red-colored normal P_{CO_2} blood buffer bar, and the pH and HCO_3^- readings are precisely what is expected for an acute decrease in the P_{CO_2} to 25 mm Hg (see Figure 7–7). Table 7–3 lists common causes of acute alveolar hyperventilation.

Renal Compensation

In the patient who hyperventilates for a long period of time (e.g., a patient who has been overly mechanically hyperventilated for more than 24 to 48 hours), the kidneys will work to correct the increased pH by excreting excess HCO_3^- in the urine. The presence of renal compensation is verified when the reported P_{CO_2}, HCO_3^-, and pH values all intersect in the green-colored area shown in the lower right-hand corner of the $P_{CO_2}/HCO_3^-/pH$ nomogram of Figure 7–8.

Alveolar hyperventilation with partial renal compensation (also called partially compensated respiratory alkalosis) is present when the reported pH and HCO_3^- both are below the normal red-colored P_{CO_2}

FIGURE 7-6 Acute ventilatory failure with partial renal compensation (also called partially compensated respiratory acidosis) is present when the reported pH and HCO_3^- both are above the normal red-colored P_{CO_2} blood buffer bar (in the purple-colored area), but the pH is still less than normal. For example, when the P_{CO_2} is 80 mm Hg at a time when the pH is 7.30 and the HCO_3^- is 37 mEq/L, ventilatory failure with partial renal compensation is confirmed.

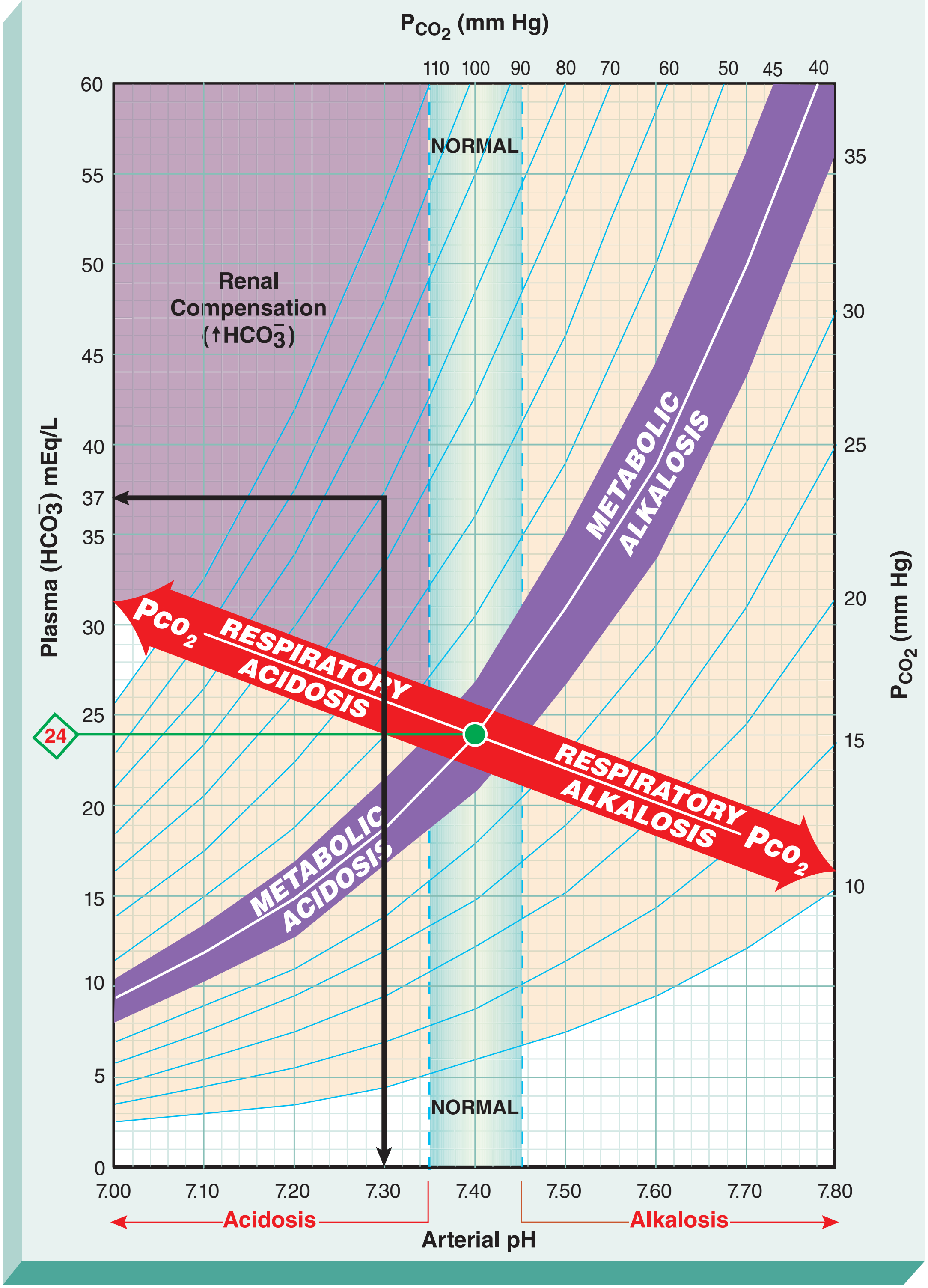
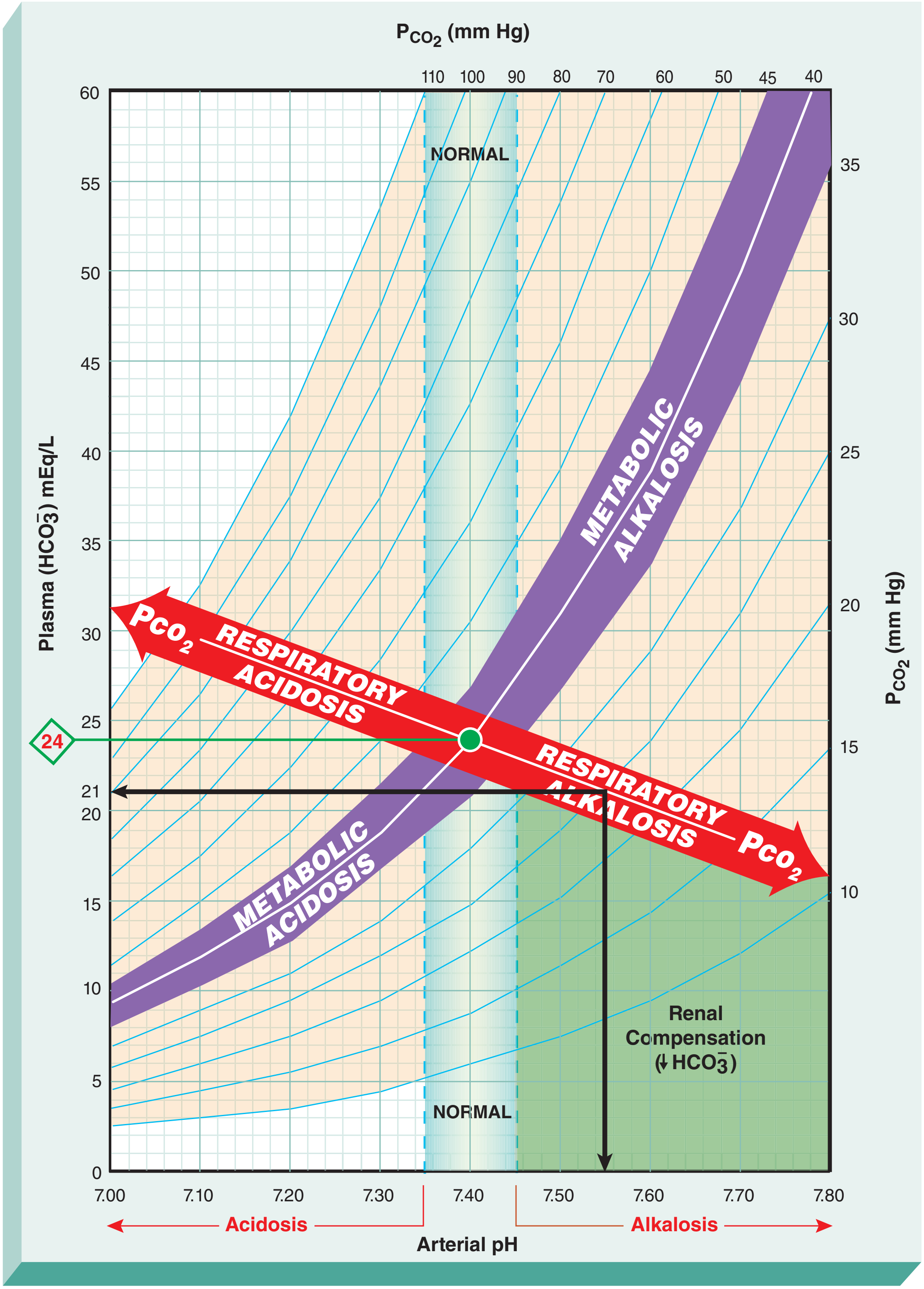


FIGURE 7-7 Acute alveolar hyperventilation is confirmed when the reported P_{CO_2}, pH, and HCO_3^- values all intersect within the red-colored "Respiratory Alkalosis" bar. For example, when the reported P_{CO_2} is 25 mm Hg at a time when the pH is 7.55 and the HCO_3 is 21 mEq/L, acute alveolar hyperventilation is confirmed.



Clinical Connection 7-3

Case Study—Chronic Ventilatory Failure (Compensated Respiratory Acidosis)

Chronic ventilatory failure—also called *compensated respiratory acidosis*—is defined as a higher than normal Pa_{CO_2}, an elevated HCO_3^- level (which compensates for the high Pa_{CO_2} level), a normal pH, and a lower than normal Pa_{O_2} level. For example, consider the following case scenario.

CASE: A 76-year-old female with a long history of chronic obstructive pulmonary disorder (COPD) enters the hospital for a routine stress test. Upon general inspection, she has a barrel chest, digital clubbing, and appears cyanotic. She is using her accessory muscles of inspiration and is pursed-lip breathing. She has a frequent cough and produces a small amount of yellow and green sputum with each coughing episode. On auscultation, she has diminished breath and heart sounds. Her past pulmonary function study records reveal severe obstructive lung function. Room air arterial blood gases (ABGs) and vital signs are as follows:

ABGs		**Vital Signs**	
pH:	7.37	Blood pressure:	130/85
Pa_{CO_2}:	76	Heart rate:	72
HCO_3^-:	44	Respiratory rate:	10
Pa_{CO_2}:	56	Temperature:	98.6°F

The clinical interpretation of the preceding ABG is **chronic ventilatory failure**—with **moderate hypoxemia** (see discussion for Figure 7–6). Although chronic ventilator failure is most commonly associated with chronic obstructive pulmonary disorders (e.g., emphysema, chronic bronchitis, bronchiectasis, and cystic fibrosis), it may also be seen in severe restrictive lung disorders. For example, chronic ventilatory failure is commonly associated with chronic tuberculosis, fungal disorders (e.g., histoplasmosis or coccidioidomycosis), kyphoscoliosis, and bronchopulmonary dysplasia.

Note the patient's low Pa_{O_2} (in this case, 56). Patients suffering from chronic ventilator failure commonly learn to live with low oxygen levels—as do normal individuals living at extremely high altitudes (e.g., in the Andes mountains that peak at 22,841 feet, or the Himalayas mountains that exceed 23,622 feet). In fact, it is common for these patients to function just fine with their day-to-day activities with this low oxygen level. For short physical excursions, however—such as going to the grocery store—they may require some low-flow oxygen via a nasal cannula and portable oxygen tank. COPD is the fourth leading cause of death, claiming more than 100,000 Americans each year. It is estimated that COPD will become the third leading cause of death by 2030.

Finally, as will be discussed in further detail in Chapter 9, chronically high Pa_{CO_2} levels can disrupt the ability of the CO_2 receptors, located in the medulla, to stimulate breathing. Patients with chronically high CO_2 levels often rely on their special oxygen-sensitive receptors—the peripheral chemoreceptors—to trigger respirations. Caution must be taken to not over-oxygenate these patients. Oxygen therapy that raises the Pa_{O_2} level above 50 to 60 mm Hg can result in apnea. Clinically, these patients are commonly referred to as CO_2 retainers and are identified by a Pa_{CO_2} above 50 mm Hg and a HCO_3^- above normal—which corrects the pH to within the normal range.

blood buffer bar (in the green-colored area), but the pH is still greater than normal. For example, when the P_{CO_2} is 20 mm Hg at a time when the pH is 7.50 and the HCO_3^- is 15 mEq/L, alveolar hyperventilation with partial renal compensation is confirmed (see Figure 7–8).

Chronic alveolar hyperventilation with complete renal compensation (also called compensated respiratory alkalosis) is present when the HCO_3^- level decreases enough to return the alkalotic pH to normal (7.45 or lower), which, in this case, would be below 14 mEq/L (see Figure 7–8).

TABLE 7-3 Common Causes of Acute Alveolar Hyperventilation

Hypoxia	Any cause of hypoxia (e.g., lung disorders, high altitudes, and heart disease) can cause acute alveolar hyperventilation.
Pain, anxiety, and fever	Relative to the degree of pain, anxiety, and fever, hyperventilation may be seen.
Brain inflammation	Relative to the degree of cerebral inflammation, hyperventilation may be seen.
Stimulant drugs	Agents such as amphetamines can cause alveolar hyperventilation

Clinical Connection 7-4

Case Study—Acute Alveolar Hyperventilation (Acute Respiratory Alkalosis)

Acute alveolar hyperventilation—also called *acute respiratory alkalosis*—is most commonly caused by **hypoxemia.** For example, consider the following case scenario.

CASE: A 16-year-old female enters the emergency room in severe respiratory distress caused by an asthmatic episode. Room air arterial blood gases (ABGs) and vital signs are as follows:

ABGs		**Vital Signs**	
pH:	7.54	Blood pressure:	145/95
Pa_{CO_2}:	27	Heart rate:	115
HCO_3^-:	22	Respiratory rate:	28
Pa_{O_2}:	58	Temperature:	98.6°F

The clinical interpretation of the above ABGs is **acute alveolar hyperventilation**—with **moderate hypoxemia** (see Figure 7–7). In this case, the patient's hypoxemia—produced by the acute asthmatic episode—caused the patient's respiratory rate to increase.

The increased respiratory rate, in turn, caused a secondary decrease in the patient's Pa_{CO_2} (in this case, 27)—which caused an acute increase in the patient's pH (in this case, 7.54). The HCO_3^- normally decreases about 2 mEq/L for every acute 10 mm Hg decrease in the P_{CO_2} level—in this case 22 (see Clinical Connection 7–1: $P_{CO_2}/HCO_3^-/pH$ Relationship—Rule of Thumb, page 320).

When the cause of acute alveolar ventilation is hypoxemia, the patient's ABGs usually return to normal once the Pa_{O_2} is therapeutically adjusted back Pa_{O_2} to the patient's normal oxygen range (80 to 100 mm Hg). Also note that the patient's blood pressure, heart rate, and respiratory rate are increased. These are common vital sign findings when there is an acute decrease in the Pa_{O_2} level. The patient's vital signs should also return back to normal once the Pa_{O_2} is corrected.

In addition to asthma, other common respiratory disorders that cause acute alveolar hyperventilation *with* hypoxemia include pneumonia, postoperative atelectasis, pulmonary edema, pneumothorax, pleural effusion, and acute respiratory distress syndrome.[3] Common causes of acute alveolar hyperventilation *without* hypoxemia include pain, anxiety, fear, brain inflammation, stimulant drugs, and metabolic acidosis. When acute alveolar hyperventilation is caused by one of these conditions, the ABG will show a normal Pa_{O_2}.

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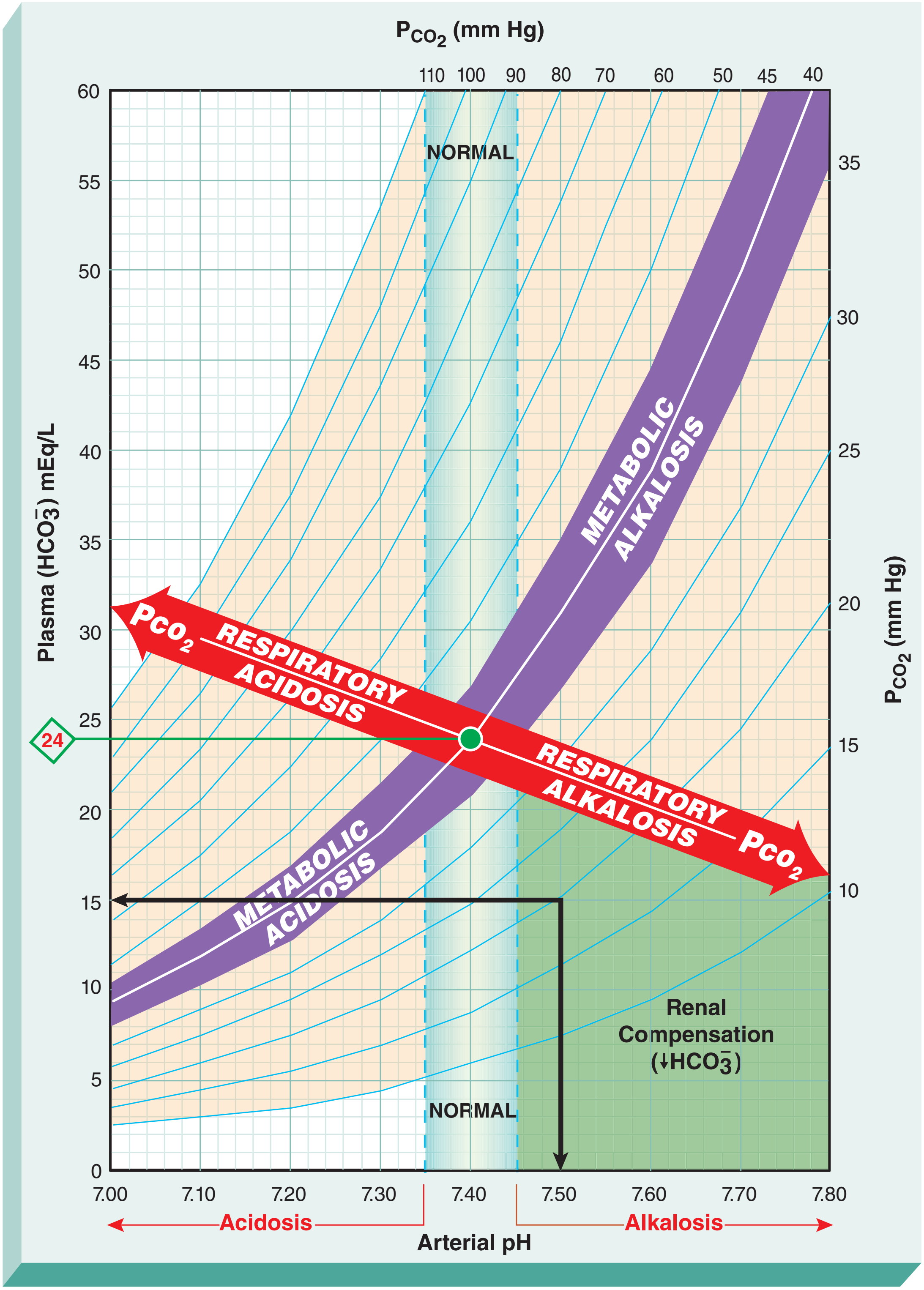
[3] When the patient becomes overly fatigued, he or she may not be able to maintain the acute alveolar hyperventilation and, therefore, may begin to hypoventilate! In such cases, the patient's ABGs will reveal the following trends: increasing Pa_{CO_2}, decreasing pH, and decreasing Pa_{O_2}—that is, acute ventilatory failure with hypoxemia (acute respiratory acidosis with hypoxemia).

FIGURE 7-8 Alveolar hyperventilation with partial renal compensation (also called partially compensated respiratory alkalosis) is present when the reported pH and HCO_3^- both are below the normal red-colored P_{CO_2} blood buffer bar (in the green-colored area), but the pH is still greater than normal. For example, when the P_{CO_2} is 20 mm Hg at a time when the pH is 7.50 and the HCO_3^- is 1 5 mEq/L, alveolar hyperventilation with partial renal compensation is confirmed.



Clinical Connection 7-5

Case Study—Chronic Alveolar Hyperventilation (Compensated Respiratory Alkalosis)

Chronic alveolar hyperventilation—also called *compensated respiratory alkalosis*—is a common baseline arterial blood gas (ABG) in the normal female during the third trimester of pregnancy. For example, consider the following case scenario.

CASE: A 27-year-old female in her third trimester of pregnancy enters the emergency room with a fractured left tibia caused by a fall on the ice. She appears short of breath, is agitated, and is complaining of severe pain. Room air ABGs and vital signs are as follows:

ABGs		**Vital Signs**	
pH:	7.43	Blood pressure:	130/85
Pa_{CO_2}:	31	Heart rate:	75
HCO_3^-:	22	Respiratory rate:	18
Pa_{O_2}:	74	Temperature:	98.6°F

The clinical interpretation of the above ABG is **chronic alveolar hyperventilation**—with **mild hypoxemia** (see discussion for Figure 7–8). During the first and second trimesters of pregnancy, it is not unusual for the Pa_{CO_2} to fall to the low 30s—for example, while exercising, walking briskly, or climbing a flight of stairs. During the third trimester of pregnancy, the Pa_{CO_2} is often consistently in the low 30s.

The chronic alveolar hyperventilation seen during the third trimester of pregnancy is most likely explained by the baby's size limiting the mother's lung expansion (which can cause a reduced Pa_{O_2} level) and the normal hormonally induced increases in ventilatory drive associated with pregnancy. Even though this patient appears short of breath, oxygen therapy is not really indicated (although it would not hurt the patient). Her agitation and appearance of respiratory distress are most likely caused by pain.

Chronic alveolar hyperventilation is also seen in patients during the early stages of chronic pulmonary disease, chronic heart failure, and in people who reside in areas of high altitudes.

General Comments

As a general rule, the kidneys do not overcompensate for an abnormal pH. That is, if the patient's blood pH becomes acidic for a long period of time due to hypoventilation, the kidneys will not retain enough HCO_3^- for the pH to climb higher than 7.40. The opposite is also true: Should the blood pH become alkalotic for a long period of time due to hyperventilation, the kidneys will not excrete enough HCO_3^- for the pH to fall below 7.40.

However, there is one important exception to this rule. In persons who chronically hypoventilate for a long period of time (e.g., patients with chronic emphysema or chronic bronchitis), it is not uncommon to find a pH greater than 7.40 (e.g., 7.43 or 7.44). This is due to water and chloride ion shifts that occur between the intercellular and extracellular spaces when the renal system works to compensate for a decreased blood pH. This action causes an overall loss of blood chloride (hypochloremia). Hypochloremia increases the blood pH.

To summarize, the lungs play an important role in maintaining the P_{CO_2}, HCO_3^-, and pH levels on a moment-to-moment basis. The kidneys, on the other hand, play an important role in balancing the HCO_3^- and pH levels during long periods of hyperventilation or hypoventilation.

Clinical Connection 7-6

Case Study—The Application of the $P_{CO_2}/HCO_3^-/pH$ Nomogram to a Victim of Carbon Monoxide Poisoning

In the Clinical Application Case 1 (page 343), the respiratory therapist is called to help care for a 36-year-old man who is overcome by carbon monoxide poisoning. The case illustrates how clinical signs and symptoms can be very misleading and how the $P_{CO_2}/HCO_3^-/pH$ nomogram can be used to help verify the cause of certain arterial blood gas findings.

Metabolic Acid–Base Imbalances

Metabolic Acidosis

The presence of other acids, not related to an increased P_{CO_2} level, can also be identified on the $P_{CO_2}/HCO_3^-/pH$ nomogram. Clinically, this condition is called **metabolic acidosis**. Metabolic acidosis is present when the P_{CO_2} reading is within the normal range (35 to 45 mm Hg) but not within the red-colored normal blood buffer line when compared to the reported HCO_3^- and pH levels. This is because the pH and HCO_3^- readings both are lower than expected for a normal P_{CO_2} level.

When the reported pH and HCO_3^- levels both are lower than expected for a normal P_{CO_2} level, the P_{CO_2} reading will drop into the purple-colored bar titled "Metabolic Acidosis" (Figure 7–9). In short, the pH, HCO_3^-, and P_{CO_2} readings will all intersect within the purple-colored "Metabolic Acidosis" bar. For example, when the reported P_{CO_2} is 40 mm Hg (normal), at a time when the pH is 7.25 and the HCO_3^- is 17 mEq/L, metabolic acidosis is confirmed (see Figure 7–9). Table 7–4 lists common causes of metabolic acidosis.

Anion Gap. The **anion gap** is used to determine if a patient's metabolic acidosis is caused by either the accumulation of fixed acids (e.g., lactic acids, keto acids, or salicylate intoxication) or an excessive loss of HCO_3^-.

According to the **law of electroneutrality**, the total number of plasma positively charged ions (cations) must equal the total number of plasma negatively charged ions (anions) in the body fluids. To determine the anion gap, the most commonly measured cations are sodium (Na^+) ions. The most commonly measured anions are the chloride (Cl^-) and bicarbonate (HCO_3^-) ions. The normal plasma concentrations of these cations and anions are as follows:

Na^+: 140 mEq/L
Cl^-: 105 mEq/L
HCO_3^-: 24 mEq/L

Mathematically, the anion gap is the calculated difference between the Na^+ ions and the sum of the HCO_3^- and Cl^- ions:

$$\begin{aligned}\text{Anion gap} &= [Na^+] - ([Cl^-] + [HCO_3^-])\\ &= 140 - (105 + 24)\\ &= 140 - 129\\ &= 11 \text{ mEq/L}\end{aligned}$$

The normal anion gap range (or the range of the unmeasured ions) is 9 to 14 mEq/L. An anion gap greater than 14 mEq/L represents metabolic acidosis.

An elevated anion gap is most commonly caused by the accumulation of fixed acids (e.g., lactic acids, ketoacids, or salicylate intoxication) in the blood. This is because the H^+ ions that are generated by the fixed acids chemically react with—and are buffered by—the plasma HCO_3^-. This action causes the HCO_3^- concentration to decrease and the anion gap to increase.

FIGURE 7-9 When the reported pH and HCO_3^- levels both are lower than expected for a normal P_{CO_2} level, the P_{CO_2} reading will drop into the purple-colored bar titled "Metabolic Acidosis." For example, when the reported P_{CO_2} is 40 mm Hg (normal) at a time when the pH is 7.25 and the HCO_3^- is 17 mEq/L, metabolic acidosis is confirmed.

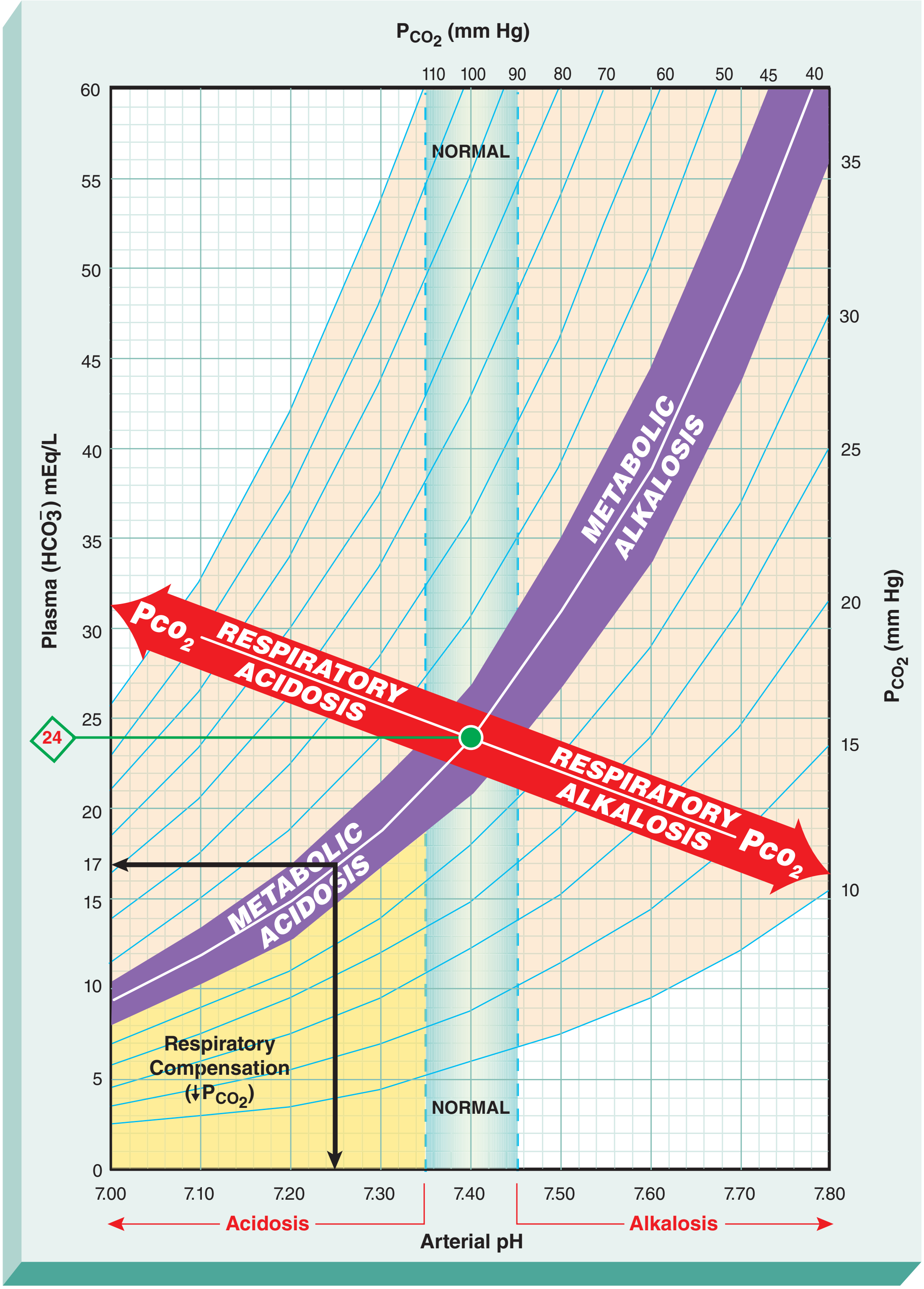


TABLE 7-4 Common Causes of Metabolic Acidosis

Lactic acidosis (fixed acids)	When the oxygen level is inadequate to meet tissue needs, alternate biochemical reactions are activated that do not utilize oxygen. This is known as **anaerobic metabolism** (non-oxygen-utilizing). Lactic acid is the end-product of this process. When these ions move into the blood, the pH decreases. Whenever an acute hypoxemia is present, the presence of lactic acids should be suspected. Lactic acids cause the anion gap to increase.
Ketoacidosis (fixed acids)	When blood insulin is low in the patient with diabetes, serum glucose cannot easily enter the tissue cells for metabolism. This condition activates alternate metabolic processes that produce **ketones** as metabolites. Ketone accumulation in the blood causes ketoacidosis. The absence of glucose because of starvation can also cause ketoacidosis. Ketoacidosis may also be seen in patients with excessive alcohol intake. The presence of ketone acids causes the anion gap to increase.
Salicylate intoxication (aspirin overdose) (fixed acids)	The excessive ingestion of aspirin leads to an increased level of salicylic acids in the blood and metabolic acidosis. Metabolic acidosis caused by salicylate intoxication causes the anion gap to increase.
Renal failure	Renal failure causes the HCO_3^- concentration to decrease and the H^+ concentration to increase. This action leads to metabolic acidosis. Metabolic acidosis caused by renal failure is associated with a normal anion gap.
Uncontrolled diarrhea	Uncontrolled diarrhea causes a loss of HCO_3^- and an increased concentration of H^+. This action leads to metabolic acidosis. Metabolic acidosis caused by severe diarrhea is associated with a normal anion gap.

Clinical Connection 7-7

Case Study—Metabolic Acidosis

Metabolic acidosis is caused by either the loss of HCO_3^- or the accumulation of **nonvolatile acids.** *Nonvolatile acids* (also called **fixed acids** or **metabolic acids**) are produced from sources other than carbon dioxide—for example, ketone acids, which are commonly associated with diabetes or starvation. The lungs do not excrete nonvolatile acids; only the renal system can excrete fixed acids. Metabolic acidosis usually stimulates a compensatory alveolar hyperventilation to lower the patient's Pa_{CO_2}—which in turn decreases the H^+ concentration. For example, consider the following case scenario.

CASE: A 31-year-old female with known insulin-dependent diabetes mellitus presented in the emergency department. She is semi-conscious and is Kussmaul breathing. Her skin is dry, and her breath has a sweet, fruity smell. Room air arterial blood gases (ABGs) and vital signs were as follows:

ABGs		**Vital Signs**	
pH:	7.26	Blood pressure:	115/70
Pa_{CO_2}:	28	Heart rate:	90
HCO_3^-:	13	Respiratory rate:	16
Pa_{O_2}:	105	Temperature:	98.6°F

The clinical interpretation of the preceding ABG is **metabolic acidosis** (see Figure 7–9). Clinically, it is not always immediately apparent what may be causing a patient's metabolic acidosis. In this case, however, based on the patient's history, the preceding ABGs, the Kussmaul breathing, and the sweet-smelling breath, it can be readily assured that the patient is suffering from **ketoacidosis** because of her diabetic crisis. The lack of insulin or a low glucose level usually causes a diabetic crisis.

Clinical Connection 7-7, Continued

When the body must use stored fats for energy—as opposed to sugars—ketones (acids) are a by-product. Ketoacidosis is commonly seen in the diabetic patient who is not eating properly or not taking his or her insulin at regular intervals.

A classic symptom of ketoacidosis is a sweet, fruity smelling breath. Another classic symptom of ketoacidosis is Kussmaul's breathing (the typical "hyperventilation" of diabetic acidosis). As discussed in Chapter 2, Kussmaul's breathing is both an increased breathing depth (hyperpnea) and an increased rate of breathing (tachypnea). This breathing pattern causes the patient's $P_{A_{CO_2}}$ and Pa_{CO_2} to decrease—decreasing the patient's overall concentration of H^+ caused by the ketone acids.

In this case, it is also interesting to note that the patient is *not* hyperventilating because of a low arterial oxygenation level. In fact, the patient's Pa_{O_2} is 105. A greater than normal Pa_{O_2}—even as high as 115 to 120 mm Hg—is not unusual in the patient with ketoacidosis—even on room air! This is because the decreased Pa_{CO_2}—caused by the Kussmaul' breathing—allows more oxygen to enter the alveoli (refer to Chapter 4, (see Table 4-1)).

Other causes of metabolic acidosis include lactic acidosis (caused by inadequate oxygen for tissue metabolism), renal failure, salicylate intoxication (aspirin overdose), and uncontrolled diarrhea.

Finally, it should be mentioned that when the metabolic acidosis is caused by lactic acids, the patient's ABG would reveal a low Pa_{O_2}. The basic cause of lactic acidosis is this: When the patient's arterial oxygen level is inadequate to meet the needs of tissue metabolism, an alternative biochemical reaction occurs that does not use oxygen. This process is called **anaerobic metabolism** (non-oxygen-using). Lactic acid is the by-product of this process. Once the patient is adequately oxygenated, the metabolic acidosis (caused by lactic acids) usually dissipates rapidly. The respiratory therapist commonly cares for patients who have lactic acidosis.

Clinically, when the patient presents with both metabolic acidosis and an increased anion gap, the respiratory therapist must investigate further to determine the source of the fixed acids. This needs to be done in order to appropriately treat the patient. For example, a metabolic acidosis caused by lactic acids justifies the need for oxygen therapy (to reverse the accumulation of the lactic acids) or one caused by ketone acids justifies the need for insulin (to reverse the accumulation of the ketone acids).

Interestingly, metabolic acidosis caused by an excessive loss of HCO_3^- (e.g., renal disease or severe diarrhea) does not cause the anion gap to increase. This is because as the HCO_3^- concentration decreases, the Cl^- concentration routinely increases to maintain electroneutrality. In other words, for each HCO_3^- that is lost, a Cl^- anion takes its place (i.e., law of electroneutrality). This action maintains a normal anion gap. Metabolic acidosis caused by a decreased HCO_3^- is often called **hyperchloremic metabolic acidosis**.

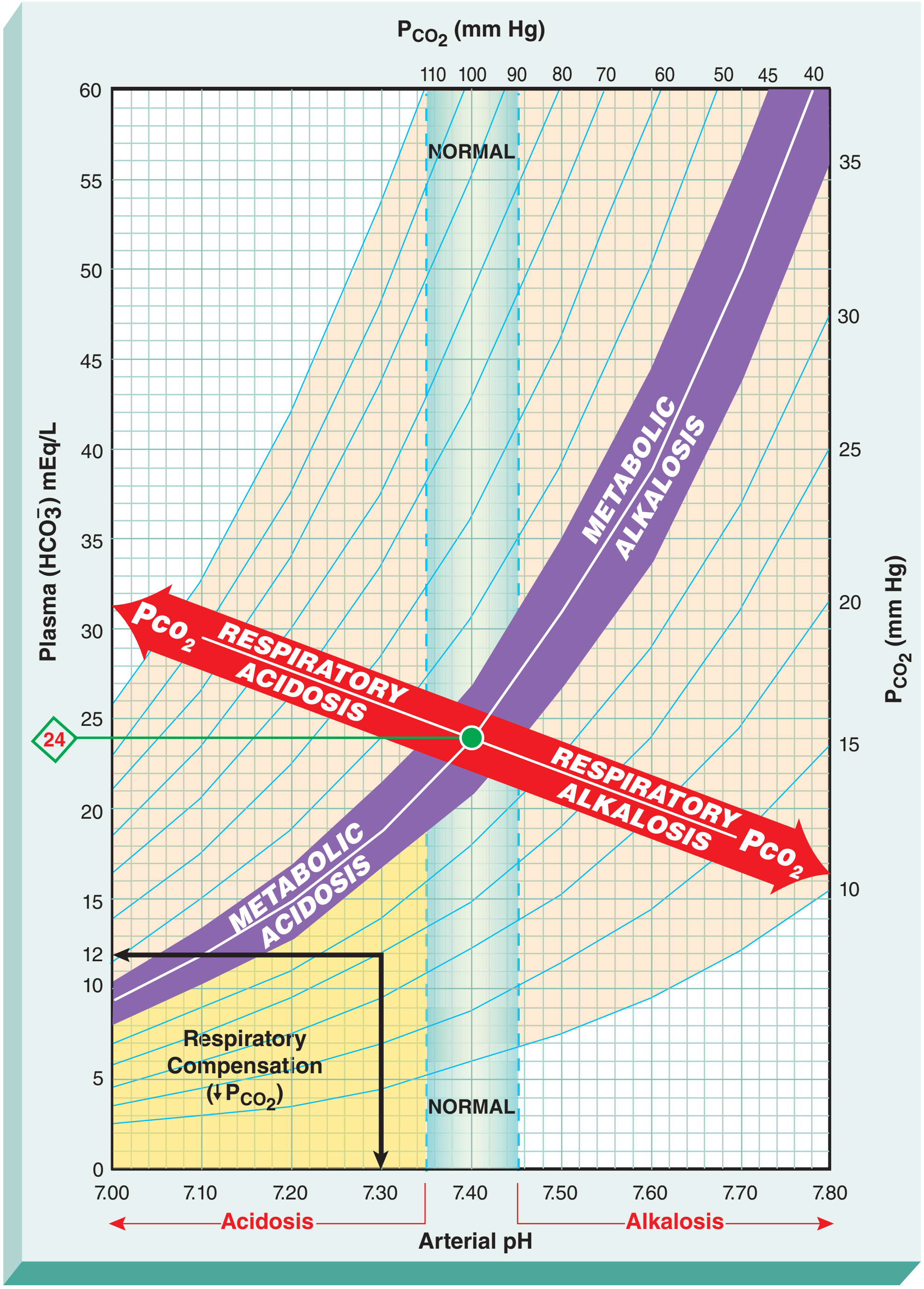
To summarize, when metabolic acidosis is accompanied by an increased anion gap, the most likely cause of the acidosis is fixed acids (e.g., lactic acids, ketoacids, or salicylate intoxication). Or, when a metabolic acidosis is seen with a normal anion gap, the most likely cause of the acidosis is an excessive loss of HCO_3^- (e.g., caused by renal disease or severe diarrhea).

Metabolic Acidosis with Respiratory Compensation

Under normal conditions, the immediate compensatory response to metabolic acidosis is an increased ventilatory rate (respiratory compensation). This action causes the Pa_{CO_2} to decline. As the P_{CO_2} decreases, the H^+ concentration decreases and, therefore, works to offset the metabolic acidosis (see Figure 7–3).

As shown in Figure 7–10, when the pH, HCO_3^-, and P_{CO_2} all intersect in the yellow-colored area of the P_{CO_2}/HCO_3^-/pH nomogram, **metabolic acidosis with partial respiratory compensation** is present. In other words, the Pa_{CO_2} has decreased below the normal range, but the pH is still below normal. For example, when the P_{CO_2} is 25 mm Hg at a time when the pH is 7.30 and the HCO_3^- is 12 mEq/L, metabolic acidosis with partial respiratory compensation is confirmed (see Figure 7–10).

FIGURE 7-10 When the pH, HCO_3^-, and P_{CO_2} all intersect in the yellow-colored area of the $P_{CO_2}/HCO_3^-/pH$ nomogram, metabolic acidosis with partial respiratory compensation is present. For example, when the P_{CO_2} is 25 mm Hg at a time when the pH is 7.30 and the HCO_3^- is 12 mEq/L, metabolic acidosis with partial respiratory compensation is confirmed.

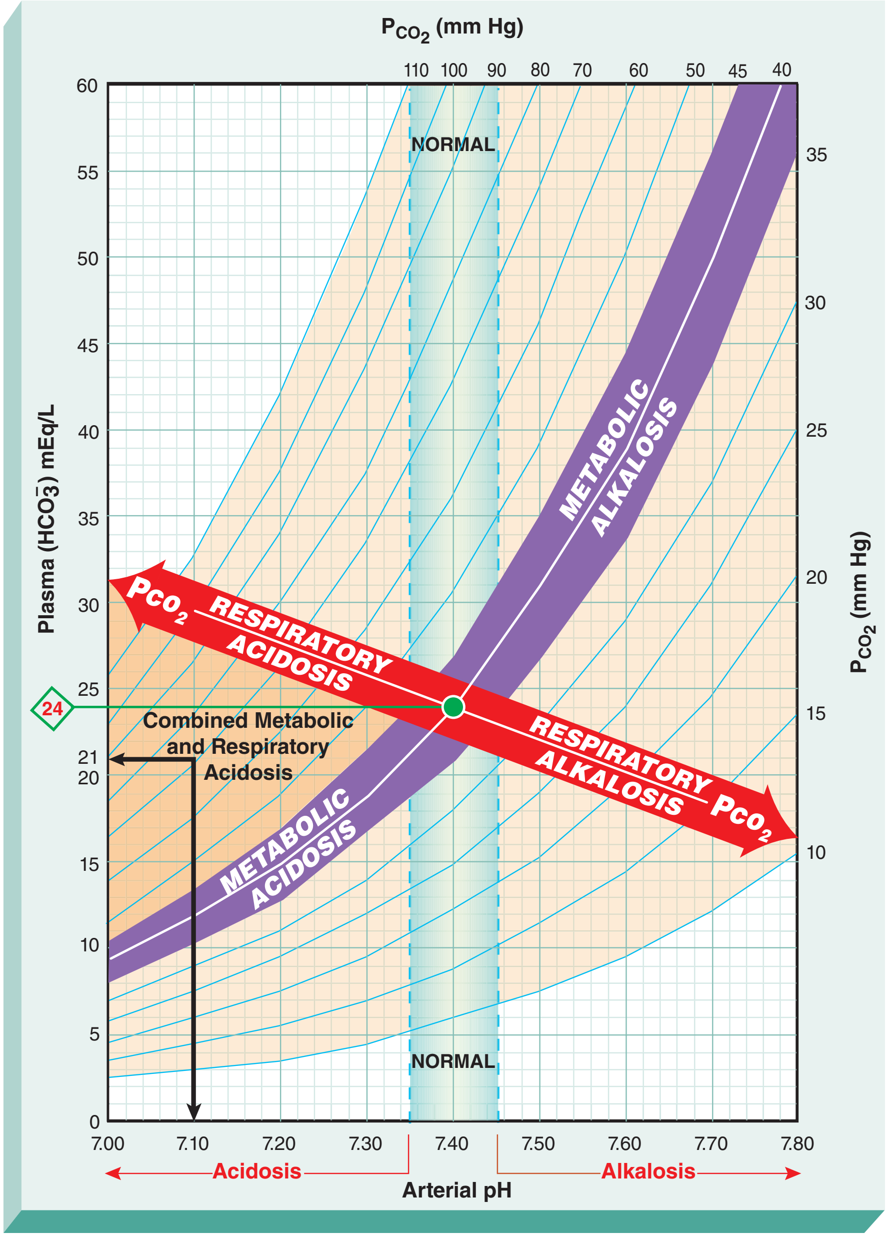


Metabolic acidosis with complete respiratory compensation is present when the P_{CO_2} decreases enough to move the acidic pH back to the normal range (7.35 or higher), which, in this case, would be below 20 mm Hg (see Figure 7–10).

Combined Metabolic and Respiratory Acidosis

When the pH, HCO_3^-, and P_{CO_2} readings all intersect in the orange-colored area of the $P_{CO_2}/HCO_3^-/pH$ nomogram, both **metabolic and respiratory acidosis** are present (Figure 7–11). For example, if the reported P_{CO_2} is 70 mm Hg at a time when the pH is 7.10 and the HCO_3^- is 21 mEq/L, both metabolic and respiratory acidosis are present (see Figure 7–11). Both metabolic and respiratory acidosis are commonly seen in patients with acute ventilatory failure, which causes the blood P_{CO_2} to increase (respiratory acidosis) and the P_{CO_2} to decrease (metabolic acidosis—caused by lactic acids).

FIGURE 7-11 When the pH, HCO_3^-, and P_{CO_2} readings all intersect in the orange-colored area of the $P_{CO_2}/HCO_3^-/pH$ nomogram, combined metabolic and respiratory acidosis are present. For example, if the reported P_{CO_2} is 70 mm Hg at a time when the pH is 7.10 and the HCO_3^- is 21 mEq/L, combined metabolic and respiratory acidosis are present.



Clinical Connection 7-8

Case Study—Combined Metabolic and Respiratory Acidosis

Combined metabolic and respiratory acidosis is commonly seen in the patient who is in severe acute ventilatory failure—that is, when the pH is low, the Pa_{CO_2} is high, and the HCO_3^- and Pa_{O_2} are severely low. In these cases, not only is the patient suffering from the acidosis, caused by a sudden rise in the Pa_{CO_2} level, but also by an additional amount of H^+ ions caused by the anaerobic metabolism—which produces lactic acids as a by-product—that occurs when a low arterial oxygen level is present. For example, consider the following case scenario.

CASE: A 17-year-old male presents in the emergency room in severe respiratory distress. The patient is well known to the hospital staff. He has a long history of asthma and has been hospitalized for exacerbation of asthma three different times over the past 4 years. In fact, during his last hospital stay, he was on a mechanical ventilator for 48 hours. On this day, the patient appears semi-conscious and cyanotic. Palpation of the chest is unremarkable. On auscultation, loud bilateral wheezes and diminished heart sounds are noted. On a 2-L nasal cannula, the arterial blood gases (ABGs) and vital signs are as follows:

ABGs		**Vital Signs**	
pH:	6.97	Blood pressure:	175/90
Pa_{CO_2}:	103	Heart rate:	110
HCO_3^-:	23	Respiratory rate:	8
Pa_{O_2}:	33(Sa_{O_2} 36%)	Temperature:	98.6°F

The clinical interpretation of the preceding ABG is **combined metabolic and respiratory acidosis** (acute ventilatory failure)—with **severe hypoxemia** (see Figure 7–11).

There are two sources responsible for the patient's acidosis—the lactic acid (caused by the low oxygen) and the acids produced by the high Pa_{CO_2} level (caused by the acute ventilatory failure). In this case, the patient needs to be immediately intubated, placed on a mechanical ventilator, and started on a regimen of first-line defense bronchodilator therapy and oxygen therapy. Time is critical! While the mechanical ventilator is being set up, the respiratory therapist should aggressively ventilate the patient with 100 percent oxygen via a bag and mask.

Overall, the respiratory therapist has two primary goals: (1) to appropriately ventilate the patient to decrease the high Pa_{CO_2} level back to the normal range (35 to 45 mm Hg) to offset the acids produced by the Pa_{CO_2}, and (2) to aggressively oxygenate the patient to offset the lactic acid produced by the anaerobic metabolism. Once the excess acids are eliminated, the patient's pH should rapidly return to normal.

The respiratory therapist should always be on the lookout for lactic acidosis when the Pa_{O_2} is severely low.

Clinical Connection 7-9

Case Study—The Application of the P_{CO_2}/HCO_3^-/pH Nomogram to a Patient with Both Respiratory and Metabolic Acidosis

In the Clinical Application Case 2 (page 344), the respiratory therapist is called to help care for a 67-year-old man in cardiac arrest. This case illustrates how the P_{CO_2}/HCO_3^-/pH nomogram can be used to confirm that the patient has a combined respiratory and metabolic acidosis and prevent the unnecessary administration of sodium bicarbonate during an emergency situation.

Metabolic Alkalosis

The presence of other bases, not related to a decreased P_{CO_2} level or renal activity, can also be identified on the $P_{CO_2}/HCO_3^-/pH$ nomogram. Clinically, this condition is called **metabolic alkalosis**. Metabolic alkalosis is present when the P_{CO_2} reading is within the normal range (35 to 45 mm Hg) but not within the red normal blood buffer line when compared to the reported pH and HCO_3^- levels. This is because the pH and HCO_3^- readings both are higher than expected for a normal P_{CO_2} level.

When the reported pH and HCO_3^- levels both are higher than expected for a normal P_{CO_2} level, the P_{CO_2} reading will move up into the purple-colored bar titled "Metabolic Alkalosis" in Figure 7–12. In other words, the pH, HCO_3^-, and P_{CO_2} readings will all intersect within the purple-colored "Metabolic Alkalosis" bar. For example, when the reported P_{CO_2} is 40 mm Hg (normal) at a time when the pH is 7.50 and the HCO_3^- is 31 mEq/L, metabolic alkalosis is confirmed (see Figure 7–12). Table 7–5 provides common causes of metabolic alkalosis.

Metabolic Alkalosis with Respiratory Compensation

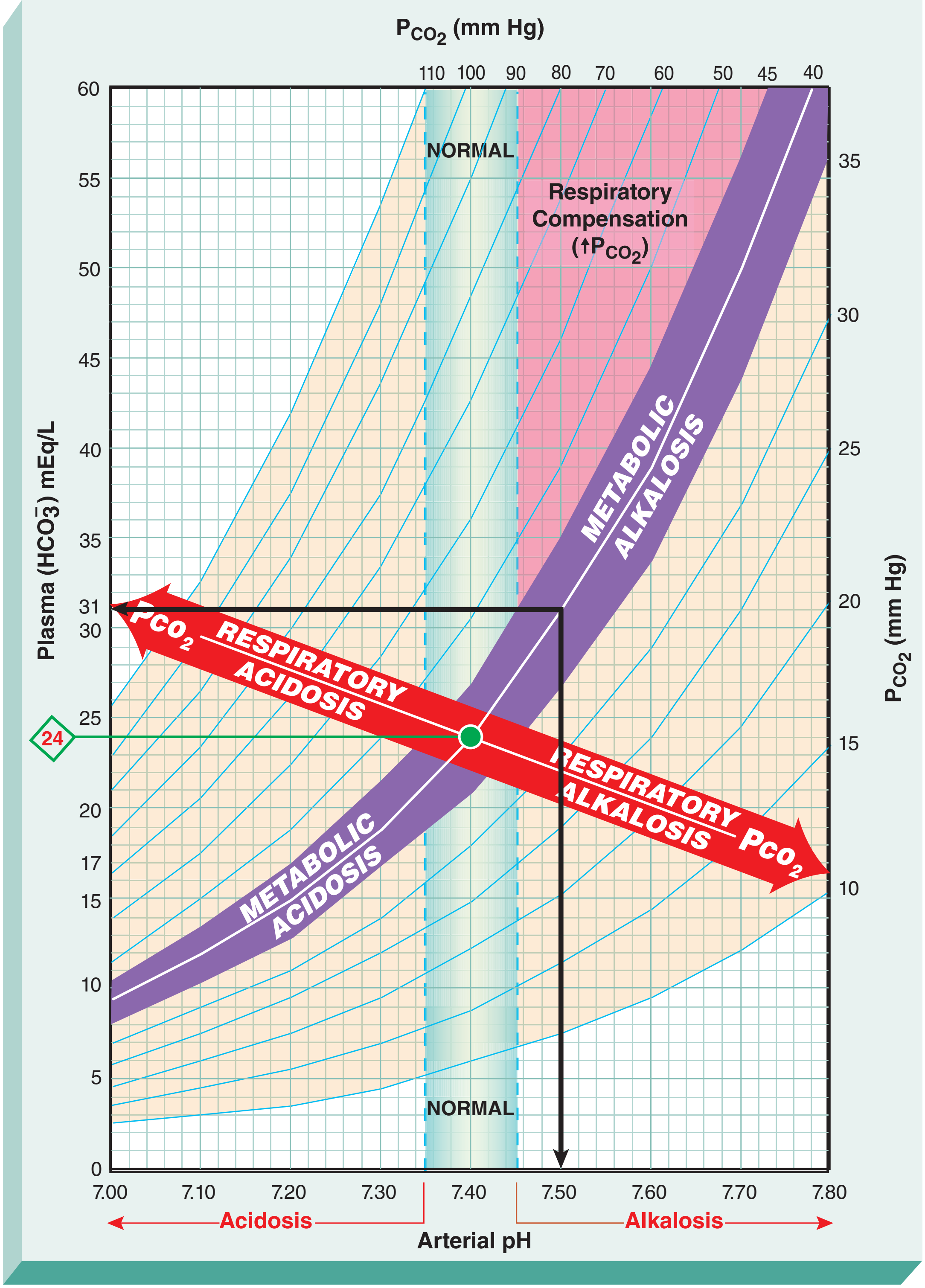
Under normal conditions, the immediate compensatory response to metabolic alkalosis is a decreased ventilatory rate (respiratory compensation). This action causes the Pa_{CO_2} to rise. As the P_{CO_2} increases, the H^+ concentration increases and, therefore, works to offset the metabolic alkalosis (see Figure 7–2).

As shown in Figure 7–13, when the pH, HCO_3^-, and P_{CO_2} all intersect in the pink-colored area of the $P_{CO_2}/HCO_3^-/pH$ nomogram, metabolic alkalosis with partial respiratory compensation is present. In other

TABLE 7-5 Common Causes of Metabolic Alkalosis

Hypokalemia	The depletion of total body potassium can occur from (1) several days of intravenous therapy without adequate replacement of potassium, (2) diuretic therapy, and (3) diarrhea. Whenever the potassium level is low, the kidneys attempt to conserve potassium by excreting hydrogen ions. This mechanism causes the blood base to increase. In addition, as the potassium level in the blood decreases, intracellular potassium moves into the extracellular space in an effort to offset the reduced potassium level in the blood serum. As the potassium (K^+) cation leaves the cell, however, a hydrogen cation (H^+) enters the cell. This mechanism causes the blood serum to become more alkalotic. Patients with hypokalemia frequently demonstrate the clinical triad of (1) metabolic alkalosis, (2) muscular weakness, and (3) cardiac dysrhythmia.
Hypochloremia	When the chloride ion (Cl^-) concentration decreases, bicarbonate ions increase in an attempt to maintain a normal cation balance in the blood serum. As the bicarbonate ion increases, the patient's blood serum becomes alkalotic. The kidneys, moreover, usually excrete potassium ions when chloride ions are unavailable, which, as described above, will also contribute to the patient's metabolic alkalosis.
Gastric suction or vomiting	Excessive gastric suction or vomiting causes a loss of hydrochloric acid (HCl) and results in an increase in blood base, that is, metabolic alkalosis.
Excessive administration of corticosteroids	Large doses of sodium-retaining corticosteroids can cause the kidneys to accelerate the excretion of hydrogen ions and potassium. Excessive excretion of either one or both of these ions will cause metabolic alkalosis.
Excessive administration of sodium bicarbonate	If an excessive amount of sodium bicarbonate is administered, metabolic alkalosis will occur. This used to occur frequently during cardiopulmonary resuscitation.
Diuretic therapy	Diuretic therapy can cause increased Cl^- and H^+ excretion and HCO_3^- retention. This condition can lead to metabolic alkalosis.
Hypovolemia	A low blood volume can lead to increased H^+ excretion and metabolic alkalosis.

FIGURE 7-12 When the reported pH and HCO_3^- levels both are higher than expected for a normal P_{CO_2} level, the P_{CO_2} reading will move up into the purple-colored bar titled “Metabolic Alkalosis.” For example, when the reported P_{CO_2} is 40 mm Hg (normal) at a time when the pH is 7.50 and the HCO_3^- is 31 mEq/L, metabolic alkalosis is confirmed.



Clinical Connection 7-10

Case Study—Metabolic Alkalosis

Metabolic alkalosis is seen more often than metabolic acidosis. Although it is not as directly life-threatening as metabolic acidosis, metabolic alkalosis is potentially dangerous. For example, consider the following case scenario.

CASE: A post-op 64-year-old female is receiving intravenous therapy over a 3-day period with an inadequate potassium (K^+) replacement. Her K^+ level is 2.8 mEq/L. An electrocardiogram reveals premature atrial and ventricular contractions. Room air arterial blood gases (ABGs) and vital signs are as follows:

ABGs		**Vital Signs**	
pH:	7.55	Blood pressure:	110/65
Pa_{CO_2}:	43	Heart rate:	84
HCO_3^-:	36	Respiratory rate:	12
Pa_{O_2}:	96	Temperature:	98.6°F

The clinical interpretation of the preceding ABG is **metabolic alkalosis** (see Figure 7–12). A lower than normal level of potassium—called **hypokalemia**—is a common cause of metabolic alkalosis and cardiac arrhythmias. Cardiac arrhythmias associated with hypokalemia include premature atrial and ventricular contractions, atrial and ventricular tachycardia, and ventricular fibrillation.

Potassium plays an important role in normal cardiac function and skeletal and smooth muscle contraction. The normal range for serum potassium levels is 3.5 to 5 mEq/L—in this case, the patient's K^+ was 2.8 mEq/L. Shortly after the attending physician corrected the patient's potassium level, both the ABG values and cardiac function returned to normal. Hypokalemia and metabolic alkalosis are common causes of muscle weakness and difficult weaning from mechanical ventilation. The student should recall that alkalosis (increased pH) shifts the oxyhemoglobin curve to the left, making it more difficult for the hemoglobin to release oxygen to the tissues.

Other causes of metabolic alkalosis include hypochloremia, gastric suction or vomiting, excessive administration of corticosteroids and sodium bicarbonate, diuretic therapy, and hypovolemia.

words, the Pa_{CO_2} has increased above the normal range, but the pH is still above normal. For example, when the P_{CO_2} is 60 mm Hg at a time when the pH is 7.50 and the HCO_3^- is 46 mEq/L, metabolic alkalosis with partial respiratory compensation is present (see Figure 7–13).

Metabolic alkalosis with complete respiratory compensation is present when the Pa_{CO_2} increases enough to move the alkalotic pH back to the normal range (7.45 or lower), which, in this case, would be above 65 to 68 mm Hg (see Figure 7–13).

Combined Metabolic and Respiratory Alkalosis

When the pH, HCO_3^-, and P_{CO_2} readings all intersect in the blue-colored area of the P_{CO_2}/HCO_3^-/pH nomogram, both **metabolic and respiratory alkalosis** are present (Figure 7–14). For example, if the reported P_{CO_2} is 25 mm Hg, at a time when pH is 7.62 and the HCO_3^- is 25 mEq/L, both metabolic and respiratory alkalosis are present (see Figure 7–14).

Base Excess/Deficit

The P_{CO_2}/HCO_3^-/pH nomogram also serves as an excellent tool to calculate the patient's total **base excess/deficit**. By knowing the base excess/deficit, nonrespiratory acid–base imbalances can be quantified. The base excess/deficit is reported in milliequivalents per liter (mEq/L) of base above or below the normal buffer base line of the P_{CO_2}/HCO_3^-/pH nomogram.

FIGURE 7-13 When the pH, HCO_3^-, and P_{CO_2} all intersect in the pink-colored area of the $P_{CO_2}/HCO_3^-/pH$ nomogram, metabolic alkalosis with partial respiratory compensation is present. For example, when the P_{CO_2} is 60 mm Hg at a time when the pH is 7.50 and the HCO_3^- is 46 mEq/L, metabolic alkalosis with partial respiratory compensation is present.

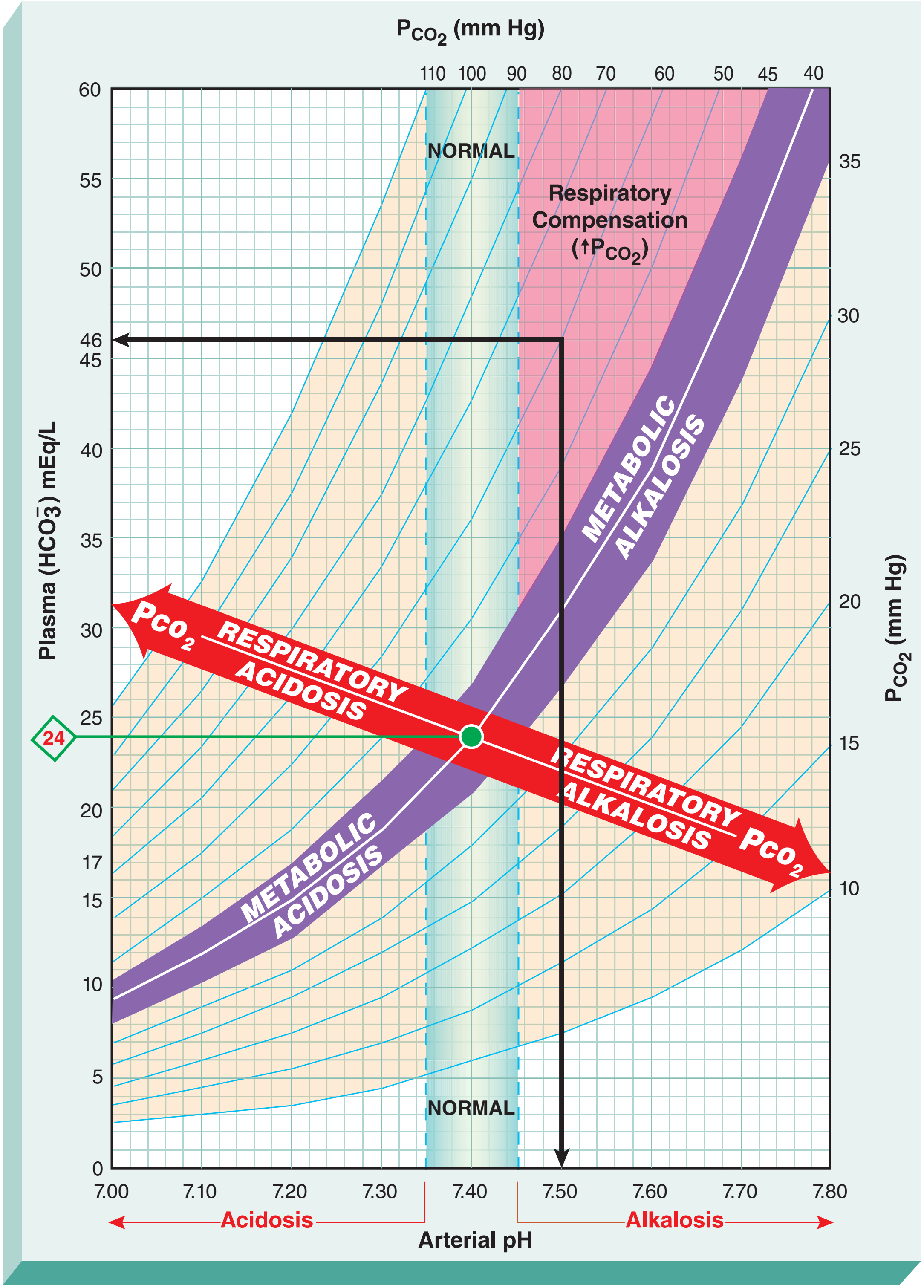
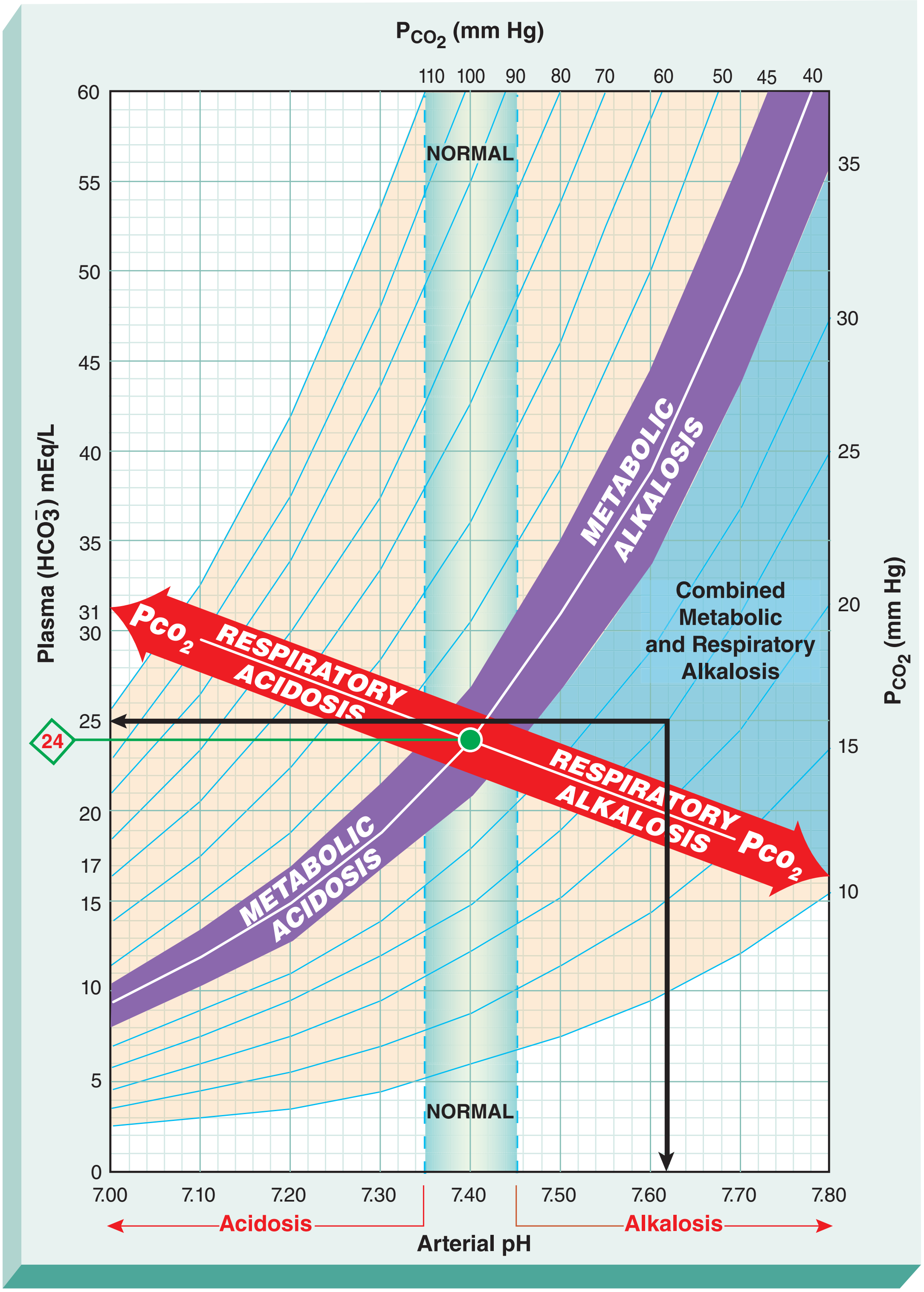


FIGURE 7-14 When the pH, HCO_3^-, and P_{CO_2} readings all intersect in the blue-colored area of the $P_{CO_2}/HCO_3^-/pH$ nomogram, combined metabolic and respiratory alkalosis are present. For example, if the reported P_{CO_2} is 25 mm Hg at a time when pH is 7.62 and the HCO_3^- is 25 mEq/L, combined metabolic and respiratory alkalosis are present.



Clinical Connection 7-11

Case Study—Combined Metabolic and Respiratory Alkalosis

Combined metabolic and respiratory alkalosis can develop when an acute decrease in Pa_{CO_2}—regardless of the reason—is accompanied by any condition that causes metabolic alkalosis, for example, hypokalemia, hypochloremia, excessive gastric suction or vomiting, excessive administration of corticosteroids or sodium bicarbonate, diuretic therapy, or hypovolemia. For example, consider the following case scenario.

CASE: This 61-year-old female automobile accident victim is in the intensive care unit on a mechanical ventilator to allow time for her double rib fractures on five adjacent ribs to heal. At this time, the mechanical ventilator is set as follows: rate—12 breaths/min, tidal volume—0.85 L, and oxygen concentration (FI_{O_2})—0.30. The morning chest radiograph reveals that her lungs are clear. For unrelated respiratory problems, she is receiving diuretic therapy, corticosteroids, and potassium to treat her hypokalemia. The patient's arterial blood gases (ABGs) and vital signs are as in the accompanying table.

ABGs		Vital Signs	
pH:	7.66	Blood pressure:	125/65
Pa_{CO_2}:	29	Heart rate:	80
HCO_3^-:	32	Respiratory rate (per ventilator):	12
Pa_{O_2}:	92	Temperature:	98.6°F

The clinical interpretation of the preceding ABG is **combined metabolic and respiratory alkalosis** (acute alveolar hyperventilation) (see discussion for Figure 7–14). The excessive HCO_3^- level is likely caused by the diuretic therapy, corticosteroids, and hypokalemia. The reduced Pa_{CO_2} is caused by overly aggressive mechanical alveolar ventilation—in this case, evidenced by a Pa_{CO_2} of 29 mm Hg.

The attending physician should be notified to correct the metabolic alkalosis problems caused by the diuretic therapy, corticosteroids, and hypokalemia. The respiratory therapist's role would be to adjust the ventilator to increase the Pa_{CO_2} back to the patient's normal range (35 to 45 mm Hg). This can easily be accomplished by either decreasing the tidal volume or decreasing the respiratory rate on the ventilator.

For example, if the pH is 7.25, and the HCO_3^- is 17 mEq/L at a time when the Pa_{CO_2} is 40 mm Hg, the $P_{CO_2}/HCO_3^-/pH$ nomogram will confirm the presence of metabolic acidosis and a base excess of –7 mEq/L (more properly called a base deficit of 7 mEq/L) (see Figure 7–9). Metabolic acidosis may be treated by the careful intravenous infusion of sodium bicarbonate ($NaHCO_3$).

In contrast, if the pH is 7.50, and the HCO_3^- is 31 mEq/L, at a time when the Pa_{CO_2} is 40 mm Hg, the $P_{CO_2}/HCO_3^-/pH$ nomogram will verify the presence of metabolic alkalosis and a base excess of 7 mEq/L (see Figure 7–12). Metabolic alkalosis is treated by correcting the underlying electrolyte problem (e.g., hypokalemia or hypochloremia) or administering ammonium chloride (NH_4Cl).

Example of Clinical Use of $P_{CO_2}/HCO_3/pH$ Nomogram

It has been shown that the $P_{CO_2}/HCO_3^-/pH$ nomogram is an excellent clinical tool to confirm the presence of (1) respiratory acid–base imbalances, (2) metabolic acid–base imbalances, or (3) a combination of a respiratory and metabolic acid–base imbalances. The clinical application cases at the end of this chapter further demonstrate the clinical usefulness of the $P_{CO_2}/HCO_3^-/pH$ nomogram.[4]

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[4] See Appendix VI for a pocket-size $P_{CO_2}/HCO_3^-/pH$ nomogram card that can be cut out, laminated, and used as a handy arterial blood gas reference tool in the clinical setting.

Chapter Summary

To fully master the clinical application of acid–base balance and the interpretation of arterial blood gases, the respiratory therapist must have a fundamental understanding of the following:

1. Acid–base balance and regulation, including the three major buffer systems
2. The $P_{CO_2}/HCO_3^-/pH$ relationship in respiratory acid–base imbalances, including acute ventilatory failure, chronic ventilatory failure and renal compensation, common causes of acute ventilatory failure, acute alveolar hyperventilation, chronic alveolar hyperventilation and renal compensation, and common causes of acute alveolar hyperventilation
3. The $P_{CO_2}/HCO_3^-/pH$ relationship in metabolic acid–base imbalances, including metabolic acidosis, common causes of metabolic acidosis, metabolic acidosis with respiratory compensation, both metabolic and respiratory acidosis, metabolic alkalosis, common causes of metabolic alkalosis, metabolic alkalosis with respiratory compensation, and both metabolic and respiratory alkalosis
4. An understanding of base excess/deficit

Clinical connections associated with these topics include (1) the $P_{CO_2}/HCO_3^-/pH$ relationship—rule of thumb, and (2) case study examples for the following arterial blood gas findings:

- Acute ventilatory failure (acute respiratory acidosis)
- Chronic ventilatory failure (compensated respiratory acidosis)
- Acute alveolar hyperventilation (acute respiratory alkalosis)
- Chronic alveolar hyperventilation (compensated respiratory alkalosis)
- The application of the $P_{CO_2}/HCO_3^-/pH$ nomogram to a victim of carbon monoxide poisoning
- Metabolic acidosis
- Combined metabolic and respiratory acidosis
- The application of the $P_{CO_2}/HCO_3^-/pH$ nomogram to a patient with both respiratory and metabolic acidosis
- Metabolic alkalosis
- Combined metabolic and respiratory alkalosis

1 Clinical Application Case

A 36-year-old man, who had been working on his car in the garage while the motor was running, suddenly experienced confusion, disorientation, and nausea. A few minutes later he started to vomit. He called out to his wife, who was nearby. Moments later he collapsed and lost consciousness. His wife called 911. Eleven minutes later, the emergency medical team (EMT) arrived, quickly assessed the patient's condition, placed a non-rebreathing oxygen mask on the patient's face, and then transported him to the ambulance. En route to the hospital, the EMT reported that the patient continued to vomit intermittently. Because of this, the patient was frequently suctioned orally to prevent aspiration.

In the emergency department, the patient's skin was cherry red. Although he was still unconscious, he

(*continued*)

Clinical Application Case 1 (continued)

was breathing on his own through a non-rebreathing oxygen mask. A medical student assigned to the emergency department stated that it appeared that the patient was being over-oxygenated—because his skin appeared cherry red—and that perhaps the oxygen mask should be removed. The respiratory therapist working with the patient strongly disagreed.

The patient's vital signs were blood pressure—165/105 mm Hg, heart rate—122 beats/min, and respirations—36 breaths/min. His arterial blood gas values on the non-rebreathing oxygen mask were pH—7.55, Pa_{CO_2}—25 mm Hg, HCO_3^-—21 mEq/L, and Pa_{O_2}—539 mm Hg. His carboxyhemoglobin level (CO_{Hb}) was 47 percent.

The patient was transferred to the intensive care unit, where he continued to be monitored closely. Although the patient never required mechanical ventilation, he continued to receive high concentrations of oxygen for the first 48 hours. By the end of the third day he was breathing room air and was conscious and able to talk with his family and the medical staff. His vital signs were blood pressure—117/77 mm Hg, heart rate—68 beats/min, and respirations—12 breaths/min. His arterial blood gas values were pH—7.4, Pa_{CO_2} —40 mm Hg, HCO_3^-—24 mEq/L, and Pa_{O_2}—97 mm Hg. His carboxyhemoglobin level (CO_{Hb}) was 3 percent. The patient was discharged on the fourth day.

Discussion

This case illustrates how clinical signs and symptoms can sometimes be very misleading and how the $P_{CO_2}/HCO_3^-/pH$ nomogram can be used to determine the cause of certain findings on arterial blood gas analysis. Even though the patient's Pa_{O_2} reading of 539 mm Hg was very high (because of the non-rebreathing oxygen mask), the CO_{Hb} level of 47 percent had seriously impaired the patient's hemoglobin's ability to carry oxygen. In addition, any oxygen that was being carried by the hemoglobin was unable to detach itself easily from the hemoglobin. This was because CO_{Hb} causes the oxygen dissociation curve to shift to the left (refer to Figure 6–4).

Thus, despite the fact that the patient's Pa_{O_2} was very high (539 mm Hg) in the emergency department, the patient's oxygen delivery system—and tissue oxygenation—was, in fact, very low and seriously compromised. The "cherry red" skin color noted by the medical student was a classic sign of carbon monoxide poisoning and not a sign of good skin color and oxygenation. The increased blood pressure, heart rate, and respiratory rate seen in the emergency department were compensatory mechanisms activated to counteract the decreased arterial oxygenation, that is, these mechanisms increased the total oxygen delivery (refer to D_{O_2} in Table 6–10).

Because it was reported that the patient had vomited excessively prior to the arterial blood gas sample being obtained in the emergency department, it was not readily apparent whether the high pH was a result of (1) the low Pa_{CO_2}—caused by the acute alveolar hyperventilation (which was caused by the low oxygen delivery), or (2) a combination of both the low Pa_{CO_2}, and the loss of stomach acids (caused by the vomiting). The answer to this question can be obtained by using the $P_{CO_2}/HCO_3^-/pH$ nomogram. In this case, when the pH, Pa_{CO_2}, and HCO_3^- values are applied to the $P_{CO_2}/HCO_3^-/pH$ nomogram, it can be seen that the elevated pH was due solely to the decreased level because all three variables cross through the normal buffer line (see Figure 7–7).[5]

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[5] See Appendix VI for a credit-card size $P_{CO_2}/HCO_3^-/pH$ nomogram that can be copied and laminated for use as a handy clinical reference tool.

2 Clinical Application Case

During a routine physical examination, a 67-year-old man had a cardiac arrest while performing a stress test in the pulmonary rehabilitation department. The patient had a long history of chronic bronchitis and emphysema. Although the patient had been in reasonably good health for the past 3 years, he had recently complained to his family physician of shortness of breath and heart palpitations. His physician ordered a full diagnostic evaluation of the patient, which included a complete pulmonary function study and stress test.

Clinical Application Case 2 (continued)

During the interview, the patient reported that he had not performed any form of exercise in years. In fact, he jokingly stated that whenever he would start to feel as if he should start to exercise, he would quickly sit down and the feeling would go away. The patient was about 35 pounds overweight and, during the stress test, appeared moderately ashen and diaphoretic. When the patient collapsed, a "Code Blue" was called and cardiopulmonary resuscitation was started immediately. When the Code Blue Team arrived, the patient had an oral airway in place and was being manually ventilated, with room air only, using a face mask and bag.

An intravenous infusion was started and the patient's heart activity was monitored with an electrocardiogram (ECG). An arterial blood gas sample was obtained and showed a pH of 7.10, Pa_{CO_2}—70 mm Hg, HCO_3^-—21 mEq/L, Pa_{O_2}—38 mm Hg, and Sa_{O_2}—50 percent. Upon seeing these results, the physician evaluated the patient's chest and breath sounds. It was quickly established that the patient's head was not hyperextended appropriately (which, as a result, impeded air flow through the oral and laryngeal airways). The patient's breath sounds were very diminished, and it was also noted that the patient's chest did not rise appropriately during each manual resuscitation. The patient was immediately intubated and manually ventilated with a bag and mask with an inspired oxygen concentration FI_{O_2} of 1.0. Despite the fact that the patient's pH was only 7.10 at this time, no sodium bicarbonate was administered.

Immediately after the patient was intubated, breath sounds could be heard bilaterally. Additionally, the patient's chest could be seen to move upward during each manual ventilation, and his skin started to turn pink. Another arterial blood sample was then drawn. While waiting for the arterial blood gas analysis results, epinephrine and norepinephrine were administered. Moments later, normal ventricular activity was seen. The arterial blood gas values from the second sample were pH—7.44, Pa_{CO_2}—35 mm Hg, HCO_3^-—24 mEq/L, Pa_{O_2}—360 mm Hg, and Sa_{O_2}—98 percent. Thirty minutes later, the patient was breathing spontaneously on an FI_{O_2} of 0.4, and he was conscious and alert. Two hours later, it was determined that the patient would not require mechanical ventilation and he was extubated. The patient was discharged from the hospital on the fourth day.

Discussion

This case illustrates how the $P_{CO_2}/HCO_3^-/pH$ nomogram can be used to confirm both a respiratory and metabolic acidosis and prevent the unnecessary administration of sodium bicarbonate during an emergency situation. As a result of the cardiopulmonary arrest, the patient's Pa_{CO_2} rapidly increased while, at the same time, his pH and Pa_{O_2} decreased. Because the patient's head was not positioned correctly, the lungs were not ventilated adequately. As a result, the Pa_{CO_2}, pH, and Pa_{O_2} continued to deteriorate. Fortunately, this was discovered when the first arterial blood gas values were seen.

The fact that the initial pH (7.10) and HCO_3^- (21 mEq/L) were both lower than expected for an acute increase in the Pa_{CO_2} (70 mm Hg) suggested that there were additional acids present in the patient's blood (i.e., acids other than those produced by the increased Pa_{CO_2}). According to the $P_{CO_2}/HCO_3^-/pH$ nomogram, an increase in the patient's Pa_{CO_2} to 70 mm Hg should have caused the pH to fall to about 7.22 and the HCO_3^- level should have increased to about 28 mEq/L (see Figure 7–5). In this case, both the pH and HCO_3^- were lower than expected. According to the $P_{CO_2}/HCO_3^-/pH$ nomogram, the patient had both a respiratory and metabolic acidosis (see Figure 7–11). In this case, the most likely cause of the metabolic acidosis was the low Pa_{O_2} (38 mm Hg), which produces lactic acids (see Table 7–4).

The patient's Pa_{O_2} was low because his head was not positioned correctly—which, in turn, prevented his lungs from being adequately ventilated. In addition, this caused the patient's Pa_{CO_2} to increase (which caused the pH to fall) and the Pa_{O_2} to decrease (which produced lactic acids and caused the pH to fall even further). In this case, therefore, the treatment of choice was to correct the cause of the respiratory and metabolic acidosis. Because the cause of the respiratory and metabolic acidosis was inadequate ventilation, the treatment of choice was aggressive ventilation.

Finally, as shown by the second arterial blood gas analysis, the arterial blood gases were rapidly corrected after intubation. In fact, the patient's Pa_{O_2} was overcorrected (360 mm Hg). The patient's inspired oxygen concentration FI_{O_2} was subsequently reduced. If sodium bicarbonate had been administered to correct the patient's pH of 7.10 before the patient was appropriately ventilated, the pH and HCO_3^- readings would have been higher than normal after his Pa_{CO_2} was ventilated down from 70 mm Hg to his normal level of about 40 mm Hg.

Review Questions

1. During acute alveolar hypoventilation, the blood

1. H_2CO_3 increases
2. pH increases
3. HCO_3^- increases
4. P_{CO_2} increases

A. 2 only
B. 4 only
C. 2 and 3 only
D. 1, 3, and 4 only

2. The bulk of the CO_2 produced in the cells is transported to the lungs as

A. H_2CO_3
B. HCO_3^-
C. CO_2 and H_2O
D. Carbonic anhydrase

3. During acute alveolar hyperventilation, the blood

1. P_{CO_2} increases
2. H_2CO_3 decreases
3. HCO_3^- increases
4. pH decreases

A. 2 only
B. 4 only
C. 1 and 3 only
D. 2 and 4 only

4. In chronic hypoventilation, renal compensation has likely occurred when the

1. HCO_3^- is higher than expected for a particular P_{CO_2}
2. pH is lower than expected for a particular P_{CO_2}
3. HCO_3^- is lower than expected for a particular P_{CO_2}
4. pH is higher than expected for a particular P_{CO_2}

A. 1 only
B. 2 only
C. 1 and 4 only
D. 3 and 4 only

5. When metabolic acidosis is present, the patient's blood

1. HCO_3^- is higher than expected for a particular P_{CO_2}
2. pH is lower than expected for a particular P_{CO_2}
3. HCO_3^- is lower than expected for a particular P_{CO_2}
4. pH is higher than expected for a particular P_{CO_2}

A. 1 only
B. 2 only
C. 3 and 4 only
D. 2 and 3 only

6. Ketoacidosis can develop from

1. An inadequate oxygen level
2. Renal failure
3. An inadequate serum insulin level
4. Anaerobic metabolism
5. An inadequate serum glucose level

A. 1 only
B. 2 and 3 only
C. 4 and 5 only
D. 3 and 5 only

7. Metabolic alkalosis can develop from

1. Hyperchloremia
2. Hypokalemia
3. Hypochloremia
4. Hyperkalemia

A. 1 only
B. 4 only
C. 1 and 3 only
D. 2 and 3 only

8. Which of the following HCO_3^- to H_2CO_3 ratios represent(s) an acidic pH?

1. 18:1
2. 28:1
3. 12:1
4. 22:1

A. 1 only
B. 2 only
C. 3 only
D. 1 and 3 only

9. If a patient has a level of 70 mm Hg, what is the H_2CO_3 concentration?

A. 1.3 mEq/L
B. 1.5 mEq/L
C. 1.7 mEq/L
D. 2.1 mEq/L

10. The value of the pK in the Henderson-Hasselbalch equation is

A. 1.0
B. 6.1
C. 7.4
D. 20.1

11. Metabolic acidosis caused by a decreased HCO_3^- is often called

A. Hyperchloremic metabolic acidosis
B. Ketoacidosis
C. Hypokalemia
D. Lactic acidosis

12. Metabolic acidosis caused by fixed acids is present when the anion gap is greater than

A. 9 mEq/L
B. 14 mEq/L
C. 20 mEq/L
D. 25 mEq/L

13. What is the anion gap in the patient with the following clinical data?

Na^+	128 mEq/L
Cl^-	97 mEq/L
HCO_3^-	22 mEq/L

____

14. According to the $P_{CO_2}/HCO_3^-/pH$ nomogram shown in Figure 7–15, if the P_{CO_2} reported is 55 mm Hg at a time when the pH is 7.14 and the HCO_3^- is 18 mEq/L, what acid–base balance disturbance would be present?

____

15. According to the $P_{CO_2}/HCO_3^-/pH$ nomogram shown in Figure 7–15, if the P_{CO_2} reported is 20 mm Hg, at a time when the pH is 7.51 and the HCO_3^- is 16 mEq/L, what acid–base balance disturbance is present?

____

Clinical Application Questions

Case 1

1. In the emergency department, even though the patient's Pa_{CO_2} was very high (539 mm Hg), the CO_{Hb} level of 47 percent (enhanced ________; impaired ________) the hemoglobin's ability to carry oxygen.

2. CO_{Hb} causes the oxygen dissociation curve to shift to the ____________________________.

3. A classic sign of carbon monoxide (CO) poisoning is a skin color that is described as ____________________________________.

4. The increased blood pressure, heart rate, and respiratory rate seen in the emergency department were compensatory mechanisms activated to counteract the decreased arterial oxygenation. These mechanisms ______________.

5. Initially, it was not clear why the patient's pH was so high. What were the two possible causes for the elevated pH?

A __________________________________

B __________________________________

6. The $P_{CO_2}/HCO_3^-/pH$ nomogram verified that the sole cause of the elevated pH was due to the

____

Case 2

1. The fact that the initial pH (7.10) and HCO_3^- (21 mEq/L) were both lower than expected for an acute increase in the Pa_{CO_2} (70 mm Hg) suggested that there were additional ________________ present in the patient's blood.

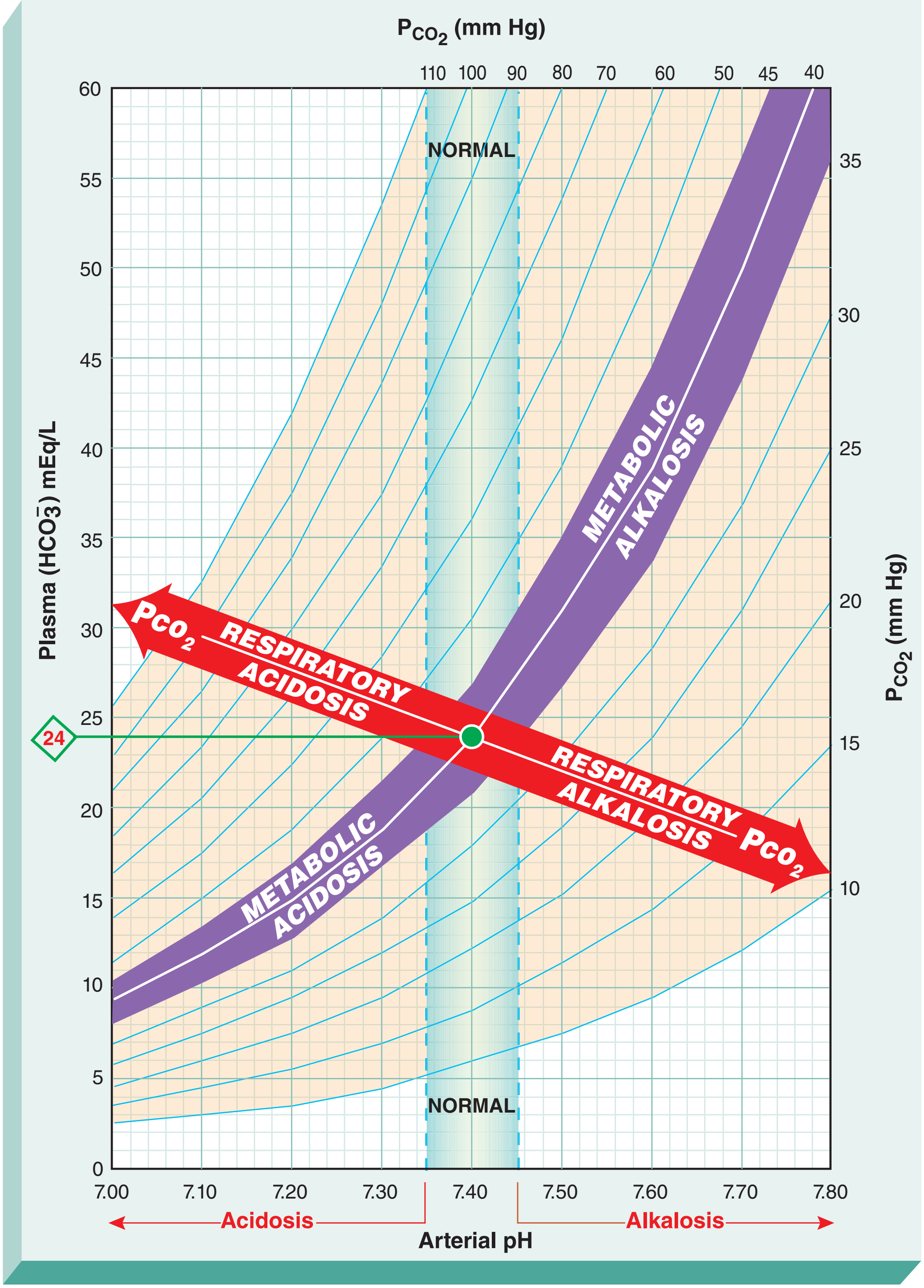
2. In this case, the most likely cause of the metabolic acidosis was the ____________________.

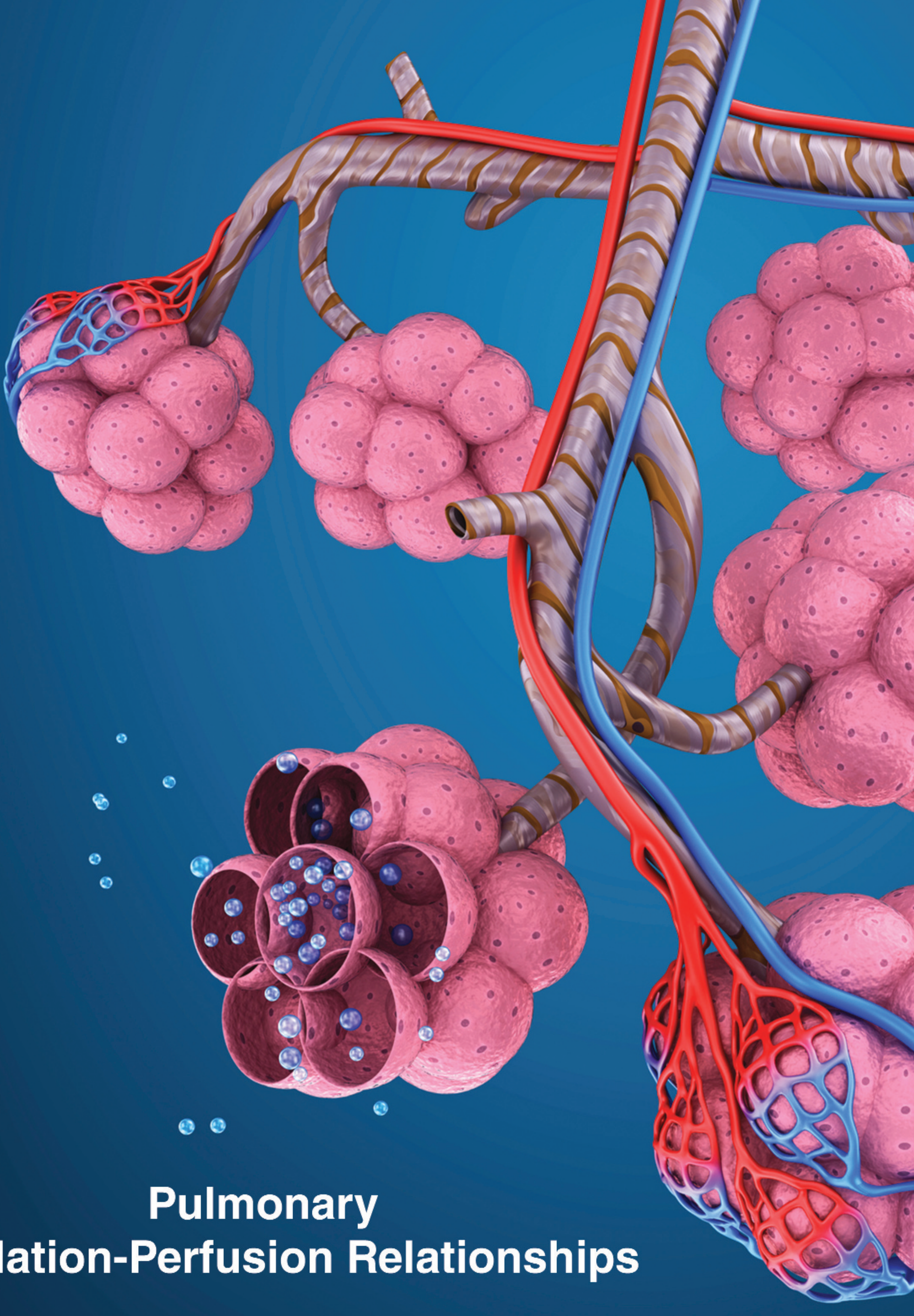
3. What was the treatment of choice in this case?

____

4. If sodium bicarbonate had initially been administered to correct the patient's low pH level, the pH and HCO_3^- readings would have been ____________________ than normal after the patient's Pa_{CO_2} had been lowered to the patient's normal level.

FIGURE 7-15 Nomogram of P_{CO_2}/HCO_3^-/pH relationship.





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Pulmonary Ventilation-Perfusion Relationships

CHAPTER 8

Ventilation-Perfusion Relationships

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Define *ventilation-perfusion ratio.*
2. Describe the overall ventilation-perfusion ratio in the normal upright lung.
3. Explain how the ventilation-perfusion ratio progressively changes from the upper to the lower lung regions in the normal upright lung.
4. Describe how an increased and decreased ventilation-perfusion ratio affects alveolar gases.
5. Describe how the ventilation-perfusion ratio affects end-capillary gases and the pH level.
6. Define *respiratory quotient.*
7. Define *respiratory exchange ratio.*
8. Identify respiratory disorders that increase the ventilation-perfusion ratio.
9. Identify respiratory disorders that decrease the ventilation-perfusion ratio.

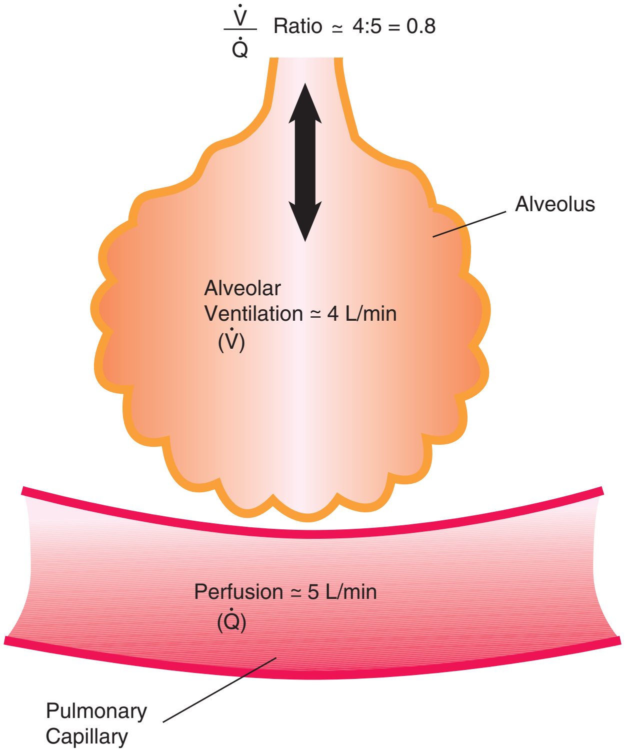
Ventilation-Perfusion Ratio

Ideally, each alveolus in the lungs should receive the same amount of ventilation and pulmonary capillary blood flow. In reality, however, this is not the case. Overall, alveolar ventilation is normally about 4 L/min and pulmonary capillary blood flow is about 5 L/min, making the average overall ratio of ventilation to blood flow 4:5, or 0.8. This relationship is called the **ventilation-perfusion ratio** ($\dot{V}/\dot{Q}$ ratio) (Figure 8–1).

Although the overall $\dot{V}/\dot{Q}$ ratio is about 0.8, the ratio varies markedly throughout the lung. In the normal individual in the upright position, the alveoli in the upper portions of the lungs (apices) receive a moderate amount of ventilation and little blood flow. As a result, the $\dot{V}/\dot{Q}$ ratio in the upper lung region is higher than 0.8.

In the lower regions of the lung, however, alveolar ventilation is moderately increased and blood flow is greatly increased because blood flow is gravity dependent. As a result, the $\dot{V}/\dot{Q}$ ratio is lower than 0.8. Thus, the $\dot{V}/\dot{Q}$ ratio progressively decreases from top to bottom in the upright lung, and the average $\dot{V}/\dot{Q}$ ratio is about 0.8 (Figure 8–2).

FIGURE 8-1 The normal ventilation-perfusion ratio ($\dot{V}/\dot{Q}$ ratio) is about 0.8.


$\frac{\dot{V}}{\dot{Q}}$ Ratio ≃ 4:5 = 0.8
Alveolus
Alveolar Ventilation ≃ 4 L/min ($\dot{V}$)
Perfusion ≃ 5 L/min ($\dot{Q}$)
Pulmonary Capillary

How the Ventilation-Perfusion Ratio Affects the Alveolar Gases

The $\dot{V}/\dot{Q}$ ratio profoundly affects the oxygen and carbon dioxide pressures in the alveoli ($P_{A_{O_2}}$ and $P_{A_{CO_2}}$). Although the normal $P_{A_{O_2}}$ and $P_{A_{CO_2}}$ are typically about 100 and 40 mm Hg, respectively, this is not the case throughout most of the alveolar units. These figures merely represent an average.

The $P_{A_{O_2}}$ is determined by the balance between (1) the amount of oxygen entering the alveoli and (2) its removal by capillary blood flow. The $P_{A_{CO_2}}$ on the other hand is determined by the balance between (1) the amount of carbon dioxide that diffuses into the alveoli from the capillary blood and (2) its removal from the alveoli by means of ventilation. Changing $\dot{V}/\dot{Q}$ ratios alter the $P_{A_{O_2}}$ and $P_{A_{CO_2}}$ levels for the reasons discussed in the following subsections.

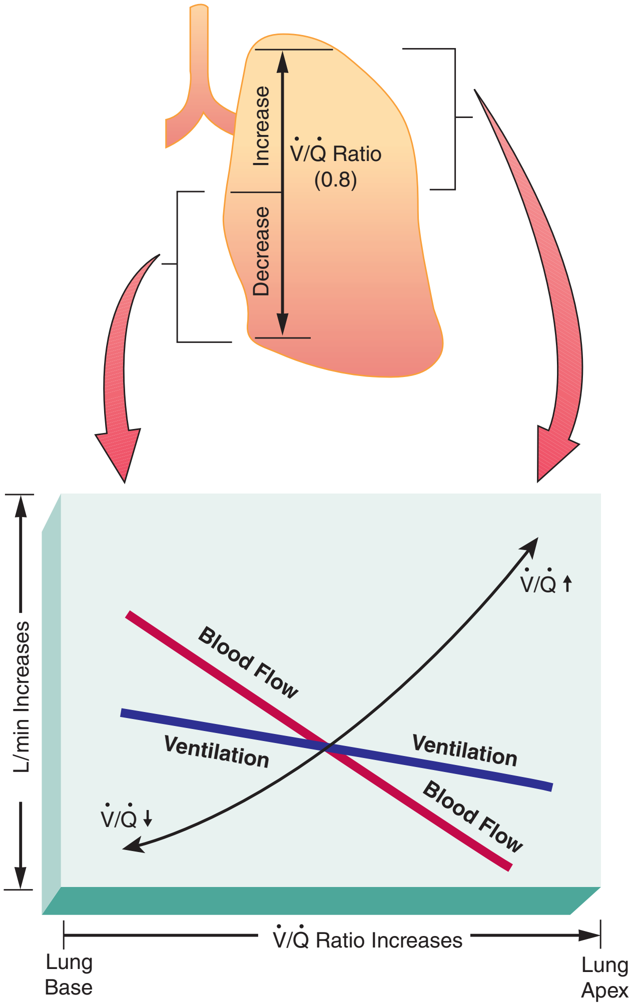
Increased $\dot{V}/\dot{Q}$ Ratio

An increased $\dot{V}/\dot{Q}$ ratio can develop from either (1) an increase in ventilation or (2) a decrease in perfusion. When the $\dot{V}/\dot{Q}$ ratio increases, the $P_{A_{O_2}}$ rises and the $P_{A_{CO_2}}$ falls. The $P_{A_{CO_2}}$ decreases because it is washed out of the alveoli faster than it is replaced by the venous blood. The $P_{A_{O_2}}$ increases because it does not diffuse into the blood[1] as fast as it enters (or is ventilated into) the alveolus (Figure 8–3). The $P_{A_{O_2}}$ also increases because the $P_{A_{CO_2}}$ decreases and, therefore, allows the $P_{A_{O_2}}$ to move closer to the partial pressure of atmospheric oxygen, which is about 159 mm Hg at sea level (refer to Table 4–1). This $\dot{V}/\dot{Q}$ relationship is present in the upper segments of the upright lung (see Figure 8–2).

---

[1] Refer to how oxygen can be classified as either perfusion or diffusion limited in Chapter 4.

FIGURE 8-2 In the upright lung, the $\dot{V}/\dot{Q}$ ratio progressively decreases from the apex to the base. Note, however, that although the $\dot{V}/\dot{Q}$ ratio in the lung bases is lower than $\dot{V}/\dot{Q}$ ratio in the lung apices, the absolute amounts of ventilation and perfusion are greatest in the lung bases of the upright lung.

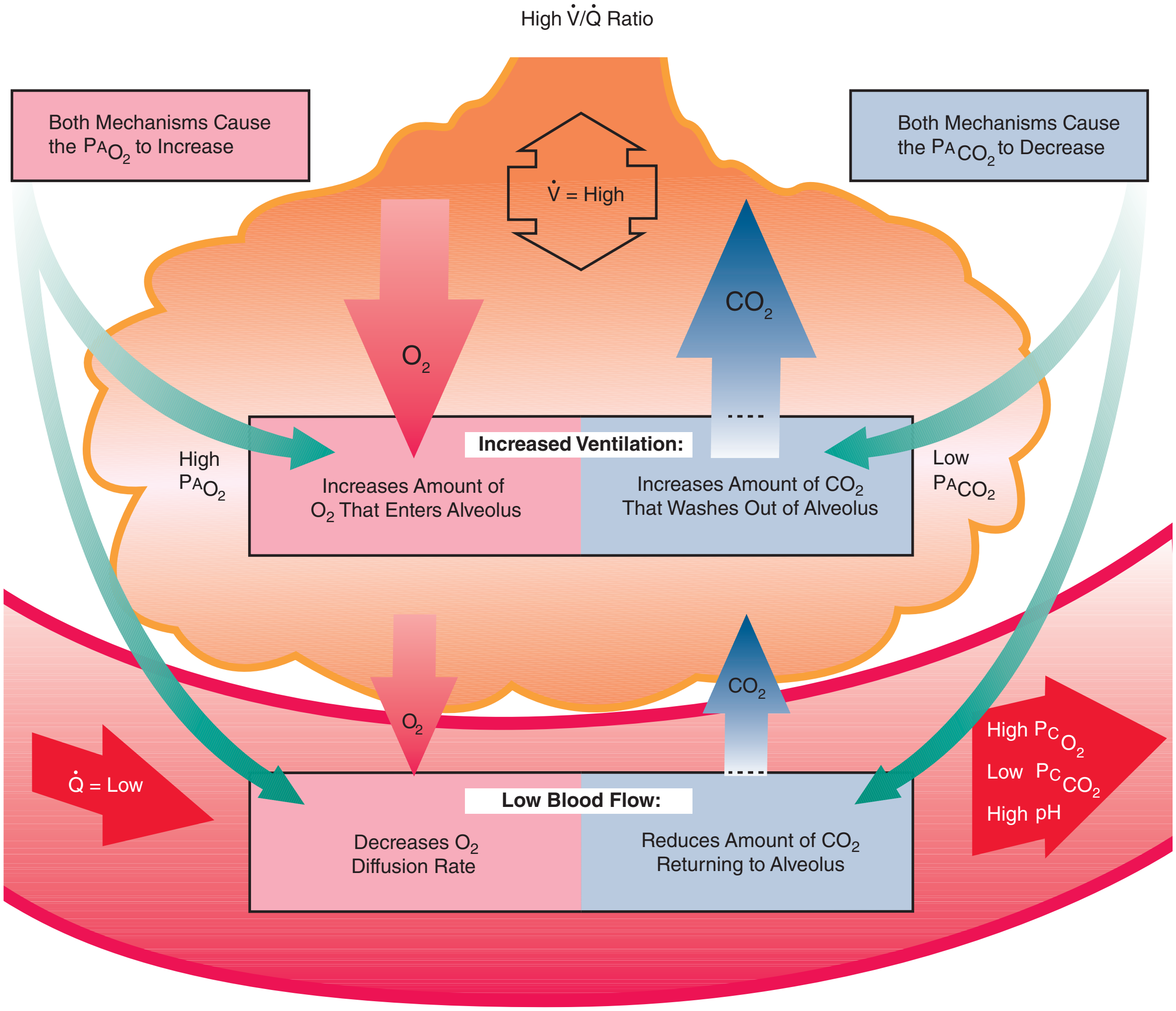

Increase
Decrease
$\dot{V}/\dot{Q}$ Ratio
(0.8)
L/min Increases
Blood Flow
Ventilation
$\dot{V}/\dot{Q}$ ↑
Ventilation
Blood Flow
$\dot{V}/\dot{Q}$ ↓
$\dot{V}/\dot{Q}$ Ratio Increases
Lung
Base
Lung
Apex

Clinical Connection 8-1

Case Study—An Increased Ventilation-Perfusion Ratio Caused by an Excessive Amount of Blood Loss

In the Clinical Application Case 1 (page 362), the respiratory therapist is called to help care for a 34-year-old male construction worker who was impaled by a steel enforcement rod. This case nicely illustrates how an increased ventilation-perfusion ratio can develop as a result of an excessive amount of blood loss. Note the following paradox in this case: Even though the patient's $P_{A_{O_2}}$ and Pa_{O_2} are higher than normal—because of the increased ventilation-perfusion ratio—the actual amount of oxygen being transported to the patient's tissue cells is lower than normal because of the decreased blood flow.

FIGURE 8-3 When the $\dot{V}/\dot{Q}$ ratio is high, the alveolar oxygen pressure ($P_{A_{O_2}}$) increases and the alveolar carbon dioxide pressure ($P_{A_{CO_2}}$) decreases.


High V̇/Q̇ Ratio
Both Mechanisms Cause the PAO2 to Increase
Both Mechanisms Cause the PACO2 to Decrease
V̇ = High
CO2
O2
High PAO2
Increased Ventilation:
Increases Amount of O2 That Enters Alveolus
Increases Amount of CO2 That Washes Out of Alveolus
Low PACO2
O2
CO2
Q̇ = Low
Low Blood Flow:
Decreases O2 Diffusion Rate
Reduces Amount of CO2 Returning to Alveolus
High PcO2
Low PcCO2
High pH

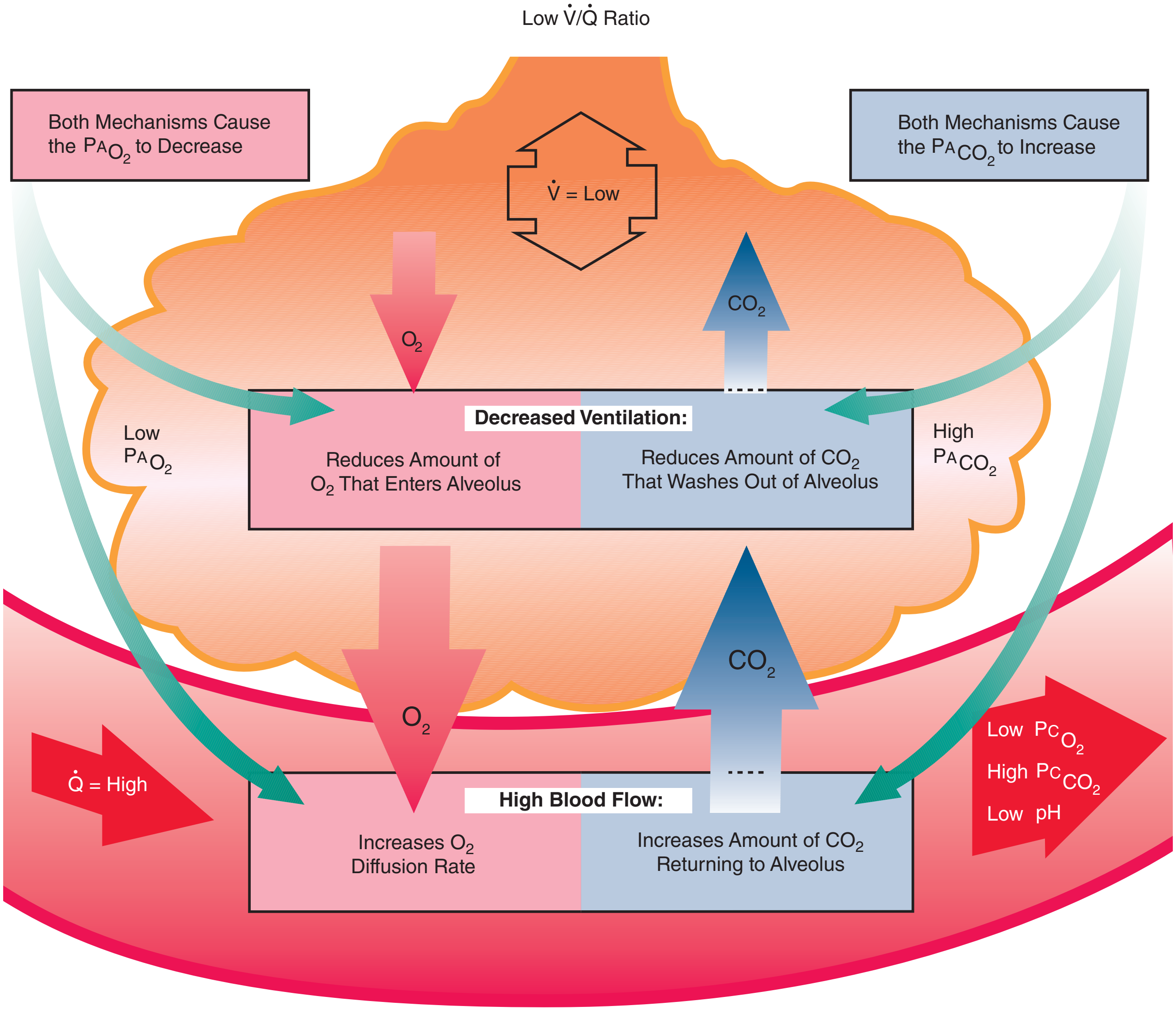
Decreased $\dot{V}/\dot{Q}$ Ratio

A decreased $\dot{V}/\dot{Q}$ ratio can develop from either a decrease in ventilation or an increase in perfusion. When the $\dot{V}/\dot{Q}$ ratio decreases, the $P_{A_{O_2}}$ falls and the $P_{A_{CO_2}}$ rises. The $P_{A_{O_2}}$ decreases because oxygen moves out of the alveolus and into the pulmonary capillary blood faster than it is replenished by ventilation. The $P_{A_{CO_2}}$ increases because it moves out of the capillary blood and into the alveolus faster than it is washed out of the alveolus (Figure 8–4). This $\dot{V}/\dot{Q}$ is present in the lower segments of the upright lung (see Figure 8–2).

O_2–CO_2 Diagram

The effect of changing $\dot{V}/\dot{Q}$ ratios on the $P_{A_{O_2}}$ and $P_{A_{CO_2}}$ levels is summarized in the O_2–CO_2 diagram (Figure 8–5). The lines in the chart represent all the possible alveolar gas compositions as the $\dot{V}/\dot{Q}$ ratio decreases or increases. The O_2–CO_2 diagram (nomogram) shows that in the upper lung regions, the $\dot{V}/\dot{Q}$ ratio is high, the $P_{A_{O_2}}$ is increasing, and the $P_{A_{CO_2}}$ is decreasing. In contrast, the diagram shows that in the lower lung regions, the $\dot{V}/\dot{Q}$ ratio is low, the $P_{A_{O_2}}$ is decreasing, and the $P_{A_{CO_2}}$ is increasing.

FIGURE 8-4 When the $\dot{V}/\dot{Q}$ ratio is low, the alveolar oxygen pressure ($P_{A_{O_2}}$) decreases and the alveolar carbon dioxide pressure ($P_{A_{CO_2}}$) increases.


Low $\dot{V}/\dot{Q}$ Ratio
Both Mechanisms Cause the $P_{A_{O_2}}$ to Decrease
Both Mechanisms Cause the $P_{A_{CO_2}}$ to Increase
$\dot{V}$ = Low
O_2
CO_2
Low $P_{A_{O_2}}$
High $P_{A_{CO_2}}$
Decreased Ventilation:
Reduces Amount of O_2 That Enters Alveolus
Reduces Amount of CO_2 That Washes Out of Alveolus
O_2
CO_2
$\dot{Q}$ = High
Low $P_{C_{O_2}}$
High $P_{C_{CO_2}}$
Low pH
High Blood Flow:
Increases O_2 Diffusion Rate
Increases Amount of CO_2 Returning to Alveolus

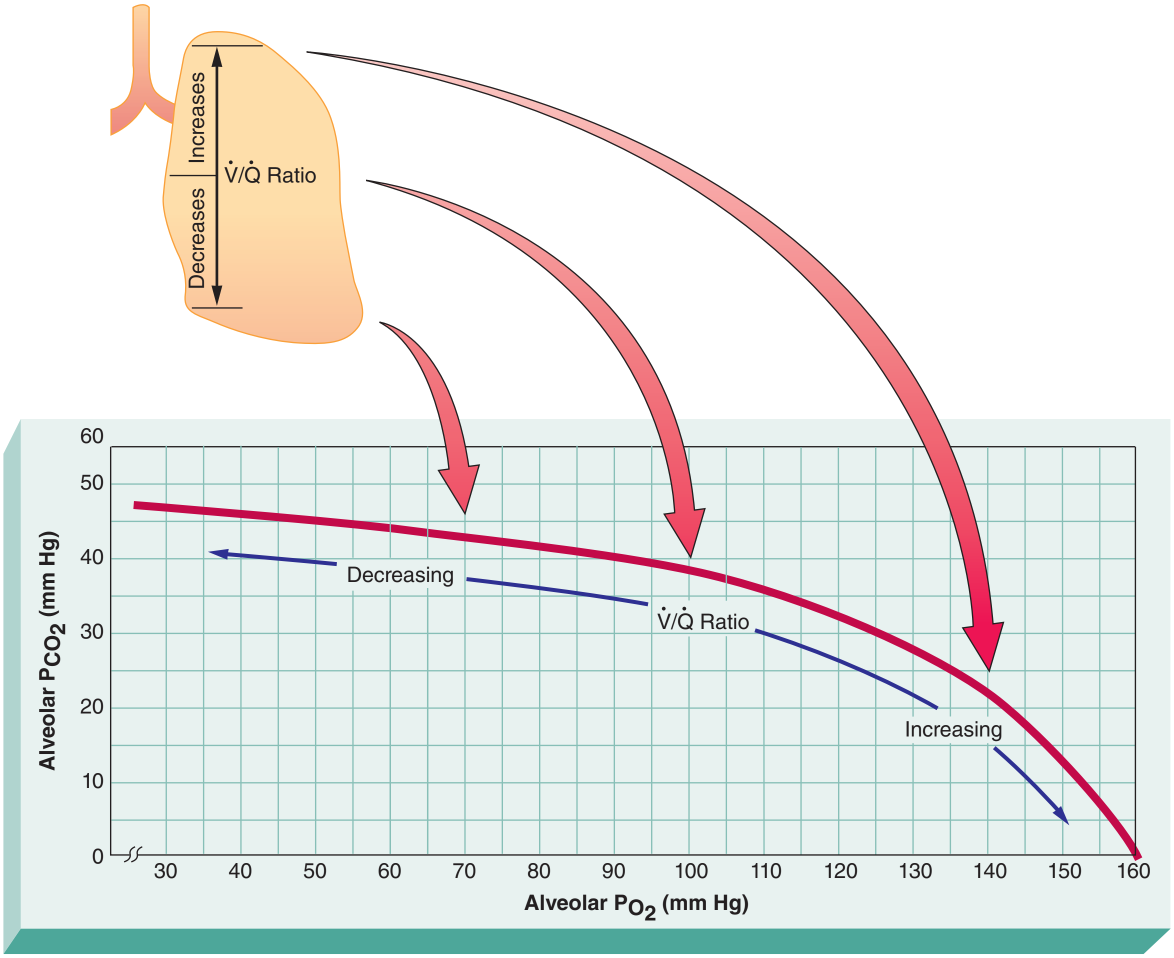
Clinical Connection 8-2

Case Study—A Decreased Ventilation-Perfusion Ratio Caused by an Upper Airway Obstruction

In the Clinical Application Case 2 (page 363), the respiratory therapist is called to help care for a 4-year-old boy who presented in the emergency department in severe respiratory distress. The boy had inhaled and lodged a quarter in his upper airway.

This case nicely illustrates how an upper airway obstruction can cause a low ventilation-perfusion ratio. Note how quickly the patient's ventilation-perfusion ratio returned to normal after the quarter was successfully removed.

FIGURE 8–5 The O_2–CO_2 diagram.



How the Ventilation-Perfusion Ratio Affects the End-Capillary Gases

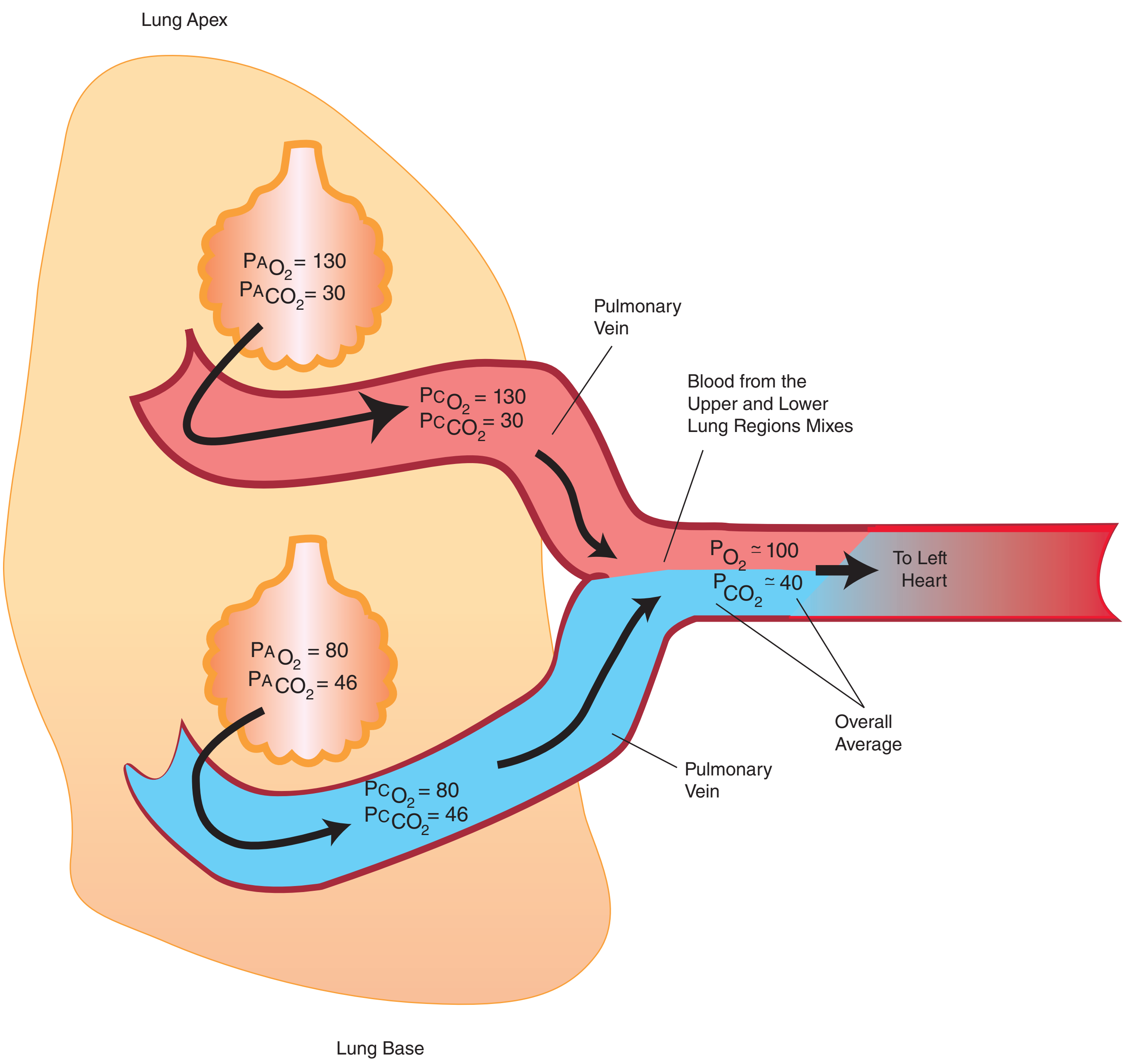
The oxygen and carbon dioxide pressures in the end-capillary blood (Pc_{O_2} and Pc_{CO_2}) mirror the PA_{O_2} and PA_{CO_2} changes that occur in the lungs. Thus, as the $\dot{V}/\dot{Q}$ ratio progressively decreases from the top to the bottom of the upright lung, causing the PA_{O_2} to decrease and the PA_{CO_2} to increase, the Pc_{O_2} and Pc_{CO_2} also decrease and increase, respectively (see Figures 8–3 and 8–4).

Downstream, in the pulmonary veins, the different Pc_{O_2} and Pc_{CO_2} levels are mixed and, under normal circumstances, produce a P_{O_2} of 100 mm Hg and a Pc_{O_2} of 40 mm Hg (Figure 8–6). The result of the Pc_{O_2} and Pc_{CO_2} mixture that occurs in the pulmonary veins is reflected downstream in the Pa_{O_2} and Pa_{CO_2} of an arterial blood gas sample (refer to Table 6–1).

Note also that as the PA_{CO_2} decreases from the bottom to the top of the lungs, the progressive reduction of the CO_2 level in the end-capillary blood causes the pH to become more alkaline. The overall pH in the pulmonary veins and, subsequently, in the arterial blood is normally about 7.35 to 7.45 (refer to Table 6–1).

Figure 8–7 summarizes the important effects of changing $\dot{V}/\dot{Q}$ ratios.

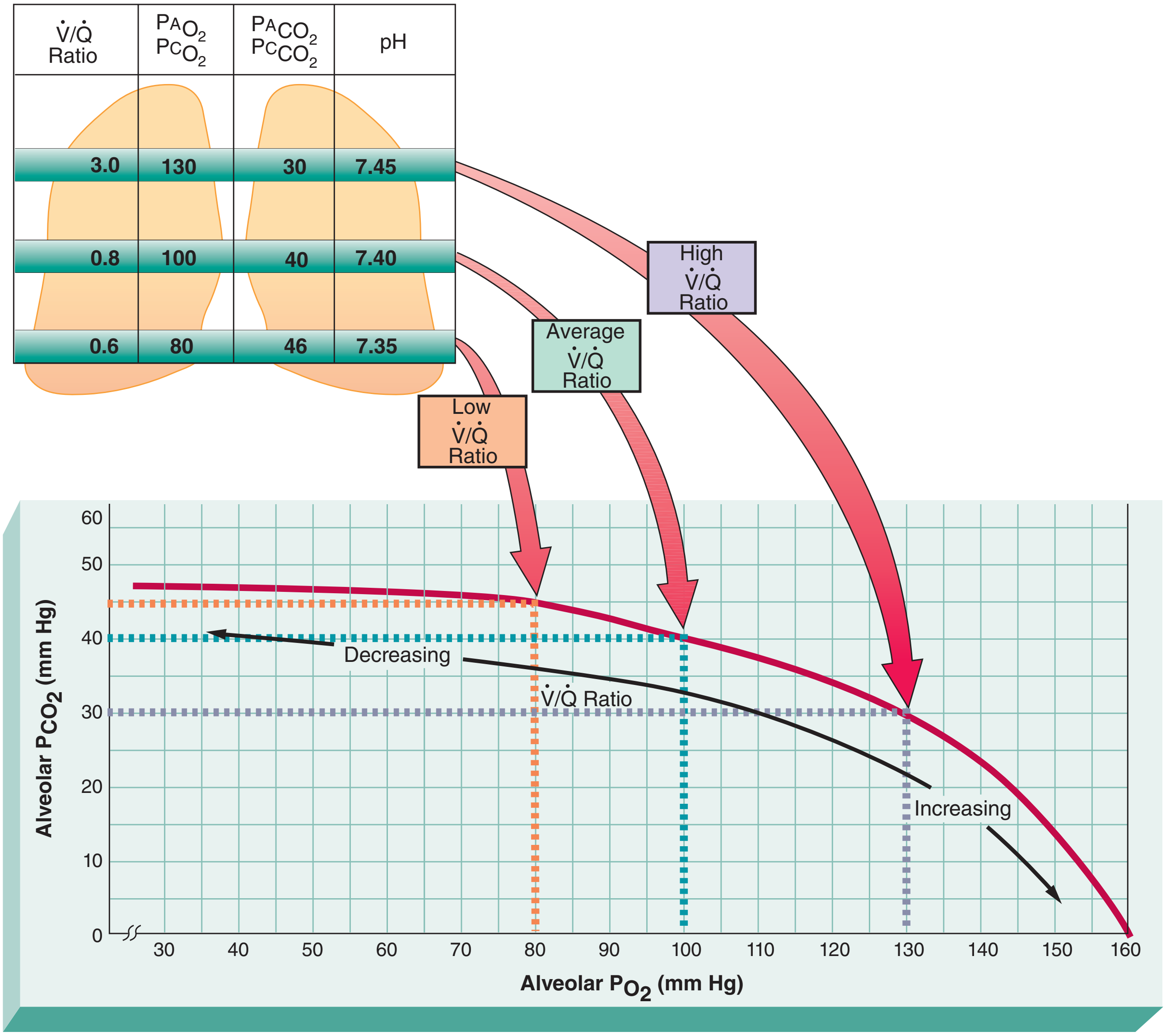
FIGURE 8-6 The mixing of pulmonary capillary blood gases (Pc_{O_2} and Pc_{CO_2}) from the upper and lower lung regions.


Lung Apex
$P_{A}O_2 = 130$
$P_{A}CO_2 = 30$
Pulmonary Vein
$Pc_{O_2} = 130$
$Pc_{CO_2} = 30$
Blood from the Upper and Lower Lung Regions Mixes
$P_{O_2} \simeq 100$
$P_{CO_2} \simeq 40$
To Left Heart
$P_{A}O_2 = 80$
$P_{A}CO_2 = 46$
Overall Average
$Pc_{O_2} = 80$
$Pc_{CO_2} = 46$
Pulmonary Vein
Lung Base

Respiratory Quotient

Gas exchange between the systemic capillaries and the cells is called **internal respiration**. Under normal circumstances, about 250 mL of oxygen are consumed by the tissues during 1 minute. In exchange, the cells produce about 200 mL of carbon dioxide. Clinically, the ratio between the volume of oxygen consumed ($\dot{V}_{O_2}$)

FIGURE 8-7 How changes in the $\dot{V}/\dot{Q}$ ratio affect the $P_{A_{O_2}}$ and $P_{c_{O_2}}$, the $P_{A_{CO_2}}$ and $P_{c_{CO_2}}$, and the pH of pulmonary blood.



$\dot{V}/\dot{Q}$ Ratio	$P_{A_{O_2}}$ $P_{c_{O_2}}$	$P_{A_{CO_2}}$ $P_{c_{CO_2}}$	pH
3.0	130	30	7.45
0.8	100	40	7.40
0.6	80	46	7.35

and the volume of carbon dioxide produced ($\dot{V}_{CO_2}$) is called the **respiratory quotient** (RQ) and is expressed as follows:

$$
\begin{aligned}
RQ &= \frac{\dot{V}_{CO_2}}{\dot{V}_{O_2}} \\
&= \frac{200\ \text{mL}\ CO_2/\text{min}}{250\ \text{mL}\ O_2/\text{min}} \\
&= 0.8
\end{aligned}
$$

Respiratory Exchange Ratio

Gas exchange between the pulmonary capillaries and the alveoli is called **external respiration** because this gas exchange is between the body and the external environment. The quantity of oxygen and carbon dioxide exchanged during a period of 1 minute is called the **respiratory exchange ratio** (RR). Under normal conditions, the RR equals the RQ.

Clinical Connection 8-3[2]

Capnography

Capnography is a rapid, continuous, noninvasive monitoring and graphic display of the patient's inhaled and exhaled carbon dioxide (CO_2) plotted against time. The gas sample is usually obtained by attaching an infrared CO_2 light sensor to the end of the patient's endotracheal tube or mask. The waveform produced is called a **capnogram** (Figure 8–8). The capnogram provides (1) a *direct* measurement of the partial pressure of CO_2 (P_{CO_2}), and/or the concentration of CO_2, which is eliminated by the lungs, and (2) an *indirect* measurement of the partial pressure of the mixed venous blood CO_2 ($P\bar{v}_{CO_2}$), which is produced by the tissue cells and transport to the lungs for elimination.

The gas sample analyzed for the capnogram is called the **end-tidal CO_2 ($etCO_2$)** or the **end-tidal partial pressure of carbon dioxide (PET_{CO_2})**—see Figure 8–8D. The normal $etCO_2$ is 35 to 45 mm Hg, or about 5 percent. The normal $etCO_2$ to Pa_{CO_2} gap is 2 to 3 mm Hg. The respiratory therapist commonly uses capnography to collect important cardiopulmonary information—including the patient's ventilation-perfusion ($\dot{V}/\dot{Q}$) ratio, ventilatory pattern trends, verification of the endotracheal tube placement, the effectiveness of CPR, and CO_2 production. The following list provides a brief overview and description of the kinds of fast and reliable information that can be obtained from capnography:

- **Ventilation-perfusion ($\dot{V}/\dot{Q}$) relationship.** A number of pulmonary conditions can alter the patient's $\dot{V}/\dot{Q}$ ratio. For example, pulmonary disorders that *decrease* the patient's $\dot{V}/\dot{Q}$ ratio—and, therefore, increase the $etCO_2$ level on the capnogram—include chronic bronchitis, emphysema, and asthma. In fact, capnography is an excellent way to monitor the effectiveness of bronchodilator therapy in the patient experiencing a severe asthmatic episode. This is because bronchospasm produces the classic "shark-fin" wave form on the capnogram as the patient struggles to exhale. The shark-fin-shaped appearance is a result of the slow and uneven alveolar CO_2 emptying that causes a right shift—a more horizontal sloping—of the B-C line on the capnogram. As the bronchospasm lessens in response to the bronchodilator therapy, the B-C line moves back to its normal (i.e., more vertical) upward slope—followed by the normal flat C-D plateau line (see Figure 8–8). Other causes of an increased $etCO_2$ include hyperthermia (fever), sepsis, seizures, bicarbonate administration, and increased metabolic rates.

  Pulmonary conditions that *increase* the patient's $\dot{V}/\dot{Q}$ ratio—and, therefore, decrease the $etCO_2$ level on the capnogram—include cardiac arrest, pulmonary embolism, hypovolemia, congestive heart failure, hemorrhage, and pulmonary hypertension. Conditions that decrease or block blood flow through the lungs can greatly reduce the amount of CO_2 reaching the lungs, which in turn cause a rapid decrease in the $etCO_2$ level.
- **Monitoring the patient's ventilation.** Capnography monitors the patient's ventilation, providing a breath-by-breath trend and an early warning system of an impending respiratory crisis. Such problems include:
  - Hyperventilation—$etCO_2$ decreases
  - Hypoventilation—$etCO_2$ increases
- **Confirming, maintaining, and assisting intubation.** Continuous end-tidal CO_2 levels can confirm a tracheal intubation. Zero $etCO_2$ confirms that an endotracheal tube is incorrectly placed in the esophagus. In cases where it is difficult to visualize the vocal cords, a capnography sensor attached to

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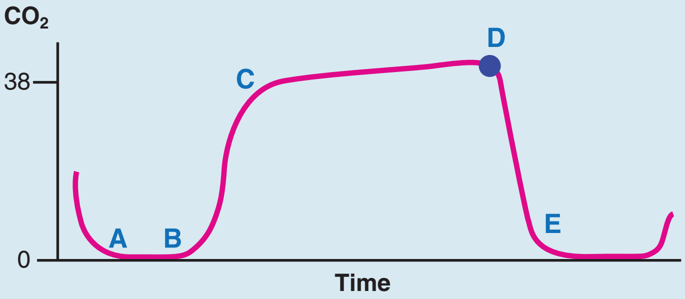
[2] Also see Clinical Connection 6–10: Capnography Ventilation vs. Oxygenation (pulse oximetry).

Clinical Connection 8-3, Continued

FIGURE 8-8 Capnogram waveform. **A** to **B** is post-inspiration (no CO_2 in inhaled gas). **B** is the beginning of alveolar exhalation (some CO_2). **B** to **C** is the exhalation upstroke where dead space gas mixes with alveolar gas (i.e., more CO_2). **C** to **D** is the continuation of exhalation with all alveolar gas (the plateau phase of the patient's exhaled CO_2 level). **D** is the end-expiration value (the peak CO_2 concentration)—this portion of the curve is commonly called the end-tidal CO_2 ($etCO_2$). Usually the end-tidal CO_2 value is used to follow the patient's ventilatory trends. The normal $etCO_2$ to $PaCO_2$ gap is 2 to 3 mm Hg. **D** to **E** reflects the inspiration phase of respiration (zero C_2 being inhaled).



the ET tube prior to intubation can assist in correctly placing the ET tube—that is, the capnogram shows a sudden rise in the $etCO_2$ level.

- **Verifying the effectiveness of CPR.** Monitoring the $etCO_2$ is a good way to assess the effectiveness of blood circulation during CPR. A rapid rise in the $etCO_2$ level may also confirm the return of spontaneous circulation during periods of no chest compressions. Or, if the $etCO_2$ suddenly drops after the CPR has been stopped, CPR may have to be restarted.
- **Monitoring sedated patients.** Capnography can be very helpful in monitoring any patient who is receiving pain management or sedation for signs of hypoventilation or apnea—that is, trends of increased $etCO_2$ levels. A sudden drop in the $etCO_2$ levels indicates the patient is beginning to arouse from sedation—that is, starting to breathe on his or her own—and will likely require more medication to prevent them from "bucking" the tube.
- **Monitoring hyperthermia.** When a patient spikes a fever, the metabolism increases and causes the $etCO_2$ to rise. Early intervention in treating fevers can be life saving.

How Respiratory Disorders Affect the $\dot{V}/\dot{Q}$ Ratio

In respiratory disorders, the $\dot{V}/\dot{Q}$ ratio is always altered. For example, in disorders that diminish pulmonary perfusion, the affected lung area receives little or no blood flow in relation to ventilation. This condition causes the $\dot{V}/\dot{Q}$ ratio to increase. As a result, a larger portion of the alveolar ventilation will not be physiologically effective and is said to be **wasted** or **dead space ventilation**. When the $\dot{V}/\dot{Q}$ ratio increases, the $P_{A_{O_2}}$ increases and the $P_{A_{CO_2}}$ decreases. Pulmonary disorders that increase the $\dot{V}/\dot{Q}$ ratio include:

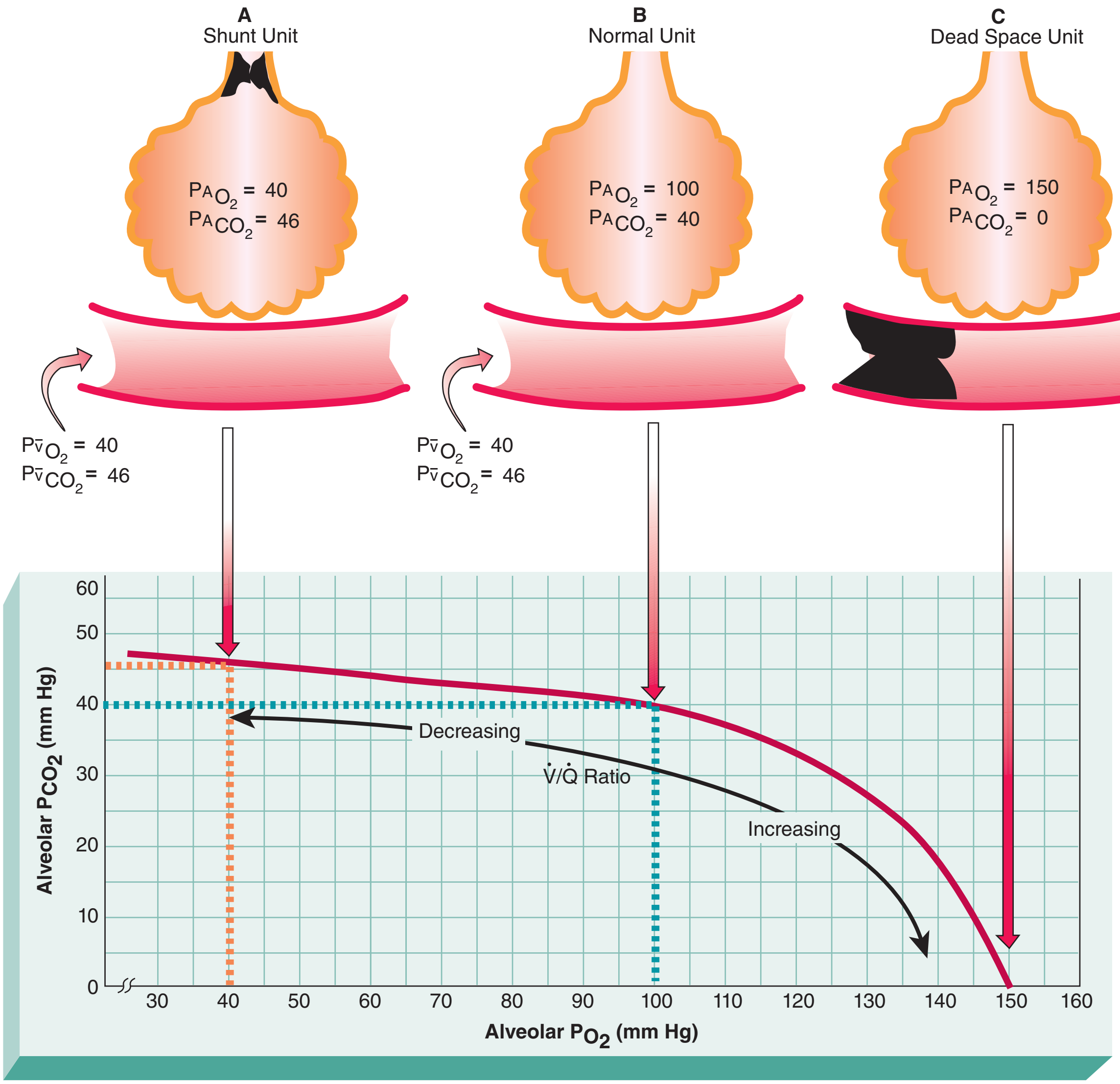
- Pulmonary emboli
- Partial or complete obstruction in the pulmonary artery or some of the arterioles (e.g., atherosclerosis, collagen disease)
- Extrinsic pressure on the pulmonary vessels (e.g., pneumothorax, hydrothorax, presence of tumor)
- Destruction of the pulmonary vessels (e.g., emphysema)
- Decreased cardiac output

In disorders that diminish pulmonary ventilation, the affected lung area receives little or no ventilation in relation to blood flow. This condition causes the $\dot{V}/\dot{Q}$ ratio to decrease. As a result, a larger portion of the pulmonary blood flow will not be physiologically effective in terms of gas exchange and is said to be **shunted blood**. When the $\dot{V}/\dot{Q}$ ratio decreases, the $P_{A_{O_2}}$ decreases and the $P_{A_{CO_2}}$ increases. Pulmonary disorders that decrease the $\dot{V}/\dot{Q}$ ratio include:

- Obstructive lung disorders (e.g., emphysema, bronchitis, asthma)
- Restrictive lung disorders (e.g., pneumonia, silicosis, pulmonary fibrosis)
- Hypoventilation from any cause

Figure 8–9 summarizes the O_2–CO_2 effects of changing $\dot{V}/\dot{Q}$ ratios in response to respiratory disorders.

FIGURE 8-9 Alveolar O_2 and CO_2 pressure changes that occur as a result of $\dot{V}/\dot{Q}$ ratio changes caused by respiratory disorders.


A
Shunt Unit
$P_{A_{O_2}}$ = 40
$P_{A_{CO_2}}$ = 46
B
Normal Unit
$P_{A_{O_2}}$ = 100
$P_{A_{CO_2}}$ = 40
C
Dead Space Unit
$P_{A_{O_2}}$ = 150
$P_{A_{CO_2}}$ = 0
$P\bar{v}_{O_2}$ = 40
$P\bar{v}_{CO_2}$ = 46
$P\bar{v}_{O_2}$ = 40
$P\bar{v}_{CO_2}$ = 46
60
50
40
30
20
10
0
Alveolar P_{CO_2} (mm Hg)
30
40
50
60
70
80
90
100
110
120
130
140
150
160
Alveolar P_{O_2} (mm Hg)
Decreasing
$\dot{V}/\dot{Q}$ Ratio
Increasing

Chapter Summary

This chapter discusses how the ventilation-perfusion $\dot{V}/\dot{Q}$ ratio can profoundly affect alveolar oxygen ($P_{A_{O_2}}$) and carbon dioxide ($P_{A_{CO_2}}$) pressures. Essential components associated with this topic include (1) how the $\dot{V}/\dot{Q}$ ratio changes from the upper to lower lung regions in the normal upright lung and (2) how an increased and decreased $\dot{V}/\dot{Q}$ ratio affects the alveolar gases and end-capillary gases and pH level. Related topics include the respiratory quotient and respiratory exchange ratio and respiratory disorders that increase the $\dot{V}/\dot{Q}$ ratio (e.g., pulmonary emboli, decreased cardiac output) and decrease the $\dot{V}/\dot{Q}$ ratio (e.g., emphysema, bronchitis, pneumonia).

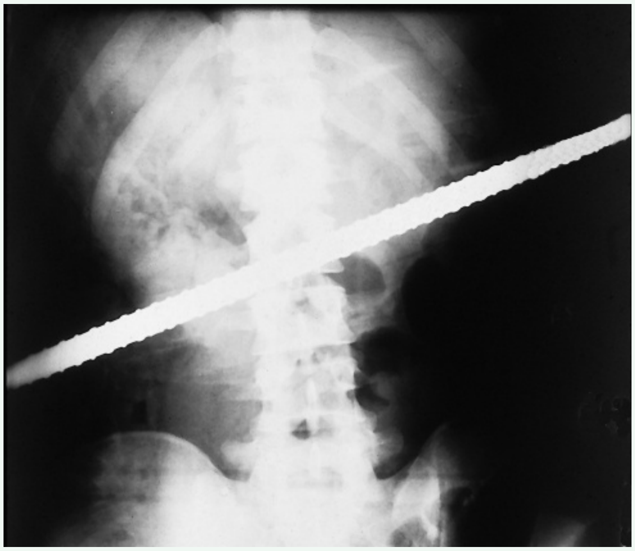
Clinical connections associated with these topics include (1) a case study illustrating an increased ventilation-perfusion ratio caused by an excessive amount of blood loss, (2) a case study describing a decreased ventilation-perfusion ratio caused by an upper airway obstruction, and (3) capnography.

1 Clinical Application Case

A 34-year-old male construction worker fell from a second-story platform and was impaled by a steel enforcement rod that was protruding vertically about 3 feet from a cement structure. The steel rod entered the side of his lower right abdomen and exited from the left side of the abdomen, about 2 cm below the 12th rib (Figure 8-10). Although the steel rod pierced the side of the descending aorta, no other major organs were seriously damaged.

The man was still conscious when workers cut through the steel rod to free him from the cement structure. While he was being cut free, an emergency medical team (EMT) inserted an intravenous infusion line, placed a non-rebreathing mask over his face, and worked to stop the bleeding as best they could. When the man was finally cut free, he was immediately transported to the trauma center. It was later estimated that he had lost about half of his blood volume at the accident site.

A full trauma team was assembled in the emergency department when the patient arrived. The patient was unconscious and very cyanotic. Even though he still had spontaneous breaths, he had an oral airway in place and was being manually ventilated with an inspired oxygen concentration $F_{I_{O_2}}$ of 1.0. His blood pressure was 65/40 mm Hg and heart rate was 120 beats/min. The respiratory therapist intubated the patient and continued manual ventilation with an $F_{I_{O_2}}$ of 1.0.


Courtesy T. Des Jardins, WindMist LLC

Almost simultaneously, a portable X-ray film was taken STAT to aid the trauma surgeons in the removal of the steel rod. A blood specimen was obtained for the following laboratory assays: glucose, BUN (blood urea nitrogen), creatinine, electrolytes, CBC (complete blood cell) count, and a type and screen and blood gas analysis. The emergency department physician called the laboratory to alert lab staff that 10 units of un-cross-matched O negative blood would be needed STAT and to stay 5 units ahead at all times. The patient was rushed to surgery. The surgical team learned during the operation that the patient's hematocrit was 15.3 percent and his hemoglobin level was 5.1 g/dL.

Four hours later, the patient was in stable condition in the surgical intensive care unit. The steel rod had been successfully removed, and his aorta was repaired. Although he was still listed in critical condition, his prognosis was described as good to excellent. At this time, however, the patient was still unconscious because of the drugs administered during surgery. He was on mechanical ventilation with the following settings: tidal volume—900 mL, respirations—12 breaths/min, $F_{I_{O_2}}$—0.4, continuous positive airway

Clinical Application Case 1 (continued)

pressure (CPAP)—5 cm H_2O, and a positive end-expiratory pressure (PEEP)—5 cm H_2O.

His blood pressure was 126/79 mm Hg and heart rate was 78 beats/min. Arterial blood gas values were pH—7.44, Pa_{CO_2}—36 mm Hg, HCO_3^-—24 mEq/L, and Pa_{O_2}—136 mm Hg. Oxygen saturation measured by pulse oximeter (Sp_{O_2}) was 98 percent. His hematocrit was 44 percent and hemoglobin level was 14.6 g/dL. The patient's recovery progressed very well. Two days later, he was conscious and no longer on the ventilator. He was discharged 6 days later.

Discussion

This case illustrates an increased ventilation-perfusion ratio caused by an excessive amount of blood lost as a result of trauma (the penetrating steel rod). As the patient continued to lose blood, the blood flow through both of his lungs progressively decreased. As a result, alveolar ventilation progressively became greater than pulmonary blood flow. Thus, the patient's alveolar ventilation was becoming more and more "ineffective" physiologically. In other words, more and more of the patient's alveolar ventilation was becoming *wasted* or *dead space ventilation*. The paradox of this condition is that even though the patient's $P_{A_{O_2}}$ and Pa_{O_2} increased in response to an increased ventilation-perfusion ratio, the actual amount of oxygen being transported decreased because of the reduced blood flow (refer to Table 6–10). Fortunately, this pathologic process was reversed in surgery.

2 Clinical Application Case

A 4-year-old boy presented in the emergency department in severe respiratory distress. An hour earlier, the patient's mother had brought home some groceries in a large box. After removing the groceries, she noticed a silver quarter in the bottom of the box. She removed the quarter and placed it on the kitchen counter. She then gave the box to her 4-year-old son to play with. Thinking he was occupied for a while, she went downstairs to the basement with her 10-year-old son to put a load of laundry in the washing machine. Moments later, they heard the youngest child cry.

Thinking that it was not anything serious, the mother asked the older boy to go get his brother. Seconds later, the older boy called to his mother that his brother looked blue and that he had vomited. The mother quickly went upstairs to the kitchen. She found her 4-year-old choking and expectorating frothy white sputum. She immediately knew what had happened. The quarter was gone. Her 4-year-old had put the quarter in his mouth and had aspirated it.

Having been trained in cardiopulmonary resuscitation (CPR), she initiated the American Heart Association's Conscious-Obstructive CPR procedure. Her son's response, however, was not favorable. In fact, his choking appeared, and sounded, worse. Frothy white secretions continued to flow out of his mouth, and a loud, brassy-like sound could be heard each time he inhaled. His inspiratory efforts were clearly labored. Alarmed, the mother immediately drove her son to the emergency department a few miles away. The 10-year-old tried to comfort his brother as they drove to the hospital.

In the emergency department, the boy was conscious, crying, and in obvious respiratory distress. His skin was cyanotic and pale. He appeared very fatigued. Inspiratory stridor could be heard without the aid of stethoscope. He was sitting up on the side of the gurney, with his legs hanging over the edge, using his accessory muscles of inspiration. His vital signs were blood pressure—89/50 mm Hg, heart rate—105 beats/min, and respirations—6 breaths/min and labored. His breath sounds were very diminished. A portable chest X-ray film showed the quarter lodged about 2 cm above the vocal cords (Figure 8-11). Oxygen saturation measured by pulse oximetry (Sp_{O_2}) was 87 percent. The patient was immediately transferred to surgery and placed under general anesthesia. The quarter was removed moments later without difficulty.

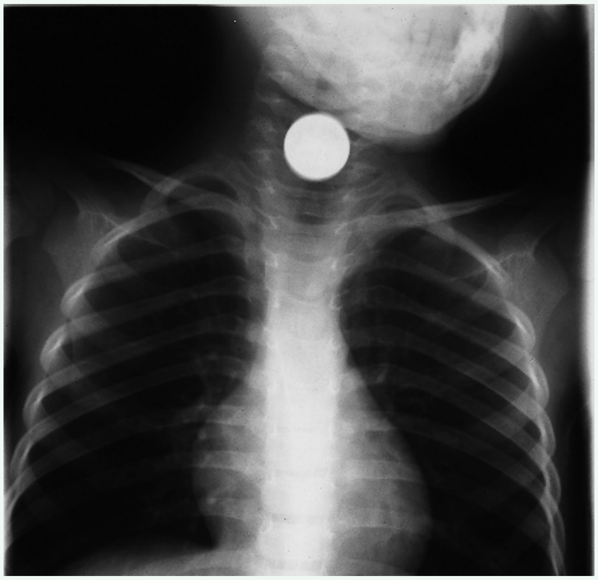
(*continued*)

Clinical Application Case 2 (continued)

Discussion

This case illustrates a decreased $\dot{V}/\dot{Q}$ ratio caused by an upper airway obstruction. Although an arterial blood sample was not drawn in this case, one can easily predict what the values would have been by considering the following factors: As a result of the upper airway obstruction, the patient had a $\dot{V}/\dot{Q}$ low ratio in both lungs. In addition, in the emergency department the patient was becoming fatigued (his respiratory rate was 6 breaths/min), which further caused the $\dot{V}/\dot{Q}$ ratio to fall.

Thus, as the patient's $\dot{V}/\dot{Q}$ ratio progressively decreased, his $P_{A_{O_2}}$ decreased while, at the same time, his $P_{A_{CO_2}}$ increased. This condition, in turn, caused the end-capillary oxygen pressure ($P_{C_{O_2}}$) and carbon dioxide pressure ($P_{C_{CO_2}}$) to decrease and increase, respectively. In addition, as the $P_{C_{CO_2}}$ decreased, the pulmonary capillary blood pH also decreased (see Figures 8–4 and 8–7). If these arterial blood gas trends had continued, the patient would have died. Fortunately, when the quarter was successfully removed, the patient's $\dot{V}/\dot{Q}$ ratio quickly returned (increased) to normal. Today, the mother has the quarter on a charm bracelet.



Courtesy T. Des Jardins, WindMist LLC

Review Questions

1. Overall, the normal $\dot{V}/\dot{Q}$ ratio is about

A. 0.2
B. 0.4
C. 0.6
D. 0.8

2. In the healthy individual in the upright position, the

1. $\dot{V}/\dot{Q}$ ratio is highest in the lower lung regions
2. $P_{A_{CO_2}}$ is lowest in the upper lung regions
3. $\dot{V}/\dot{Q}$ ratio is lowest in the upper lung regions
4. $P_{A_{CO_2}}$ is highest in the lower lung regions

A. 1 only
B. 2 only
C. 4 only
D. 3 and 4 only

3. When the $\dot{V}/\dot{Q}$ ratio decreases, the

1. $P_{A_{O_2}}$ falls
2. $P_{C_{CO_2}}$ increases
3. $P_{A_{CO_2}}$ rises
4. $P_{C_{O_2}}$ decreases

A. 1 only
B. 3 only
C. 2, 3, and 4 only
D. 1, 2, 3, and 4

4. When alveolar ventilation is 7 L/min and the pulmonary blood flow is 9.5 L/min, the $\dot{V}/\dot{Q}$ ratio is about

A. 0.4
B. 0.5
C. 0.6
D. 0.7

5. If tissue cells consume 275 mL of O_2 per minute and produce 195 mL of CO_2 per minute, what is the RQ?

A. 0.65
B. 0.7
C. 0.8
D. 0.96

Clinical Application Questions

Case 1

1. As the patient continued to lose blood, his alveolar ventilation became more and more ________________________________.

2. The patient's alveolar ventilation was ________ or ______________________ ventilation.

3. The paradox in this case was that even though the patient's $P_{A_{O_2}}$ and $P_{a_{O_2}}$ increased in response to the increased ventilation-perfusion ratio, the actual amount of oxygen being transported (_______ decreased; _______ increased; _______ remained the same) because of the (_______ increased; _______ decreased) blood flow.

Case 2

1. As a result of the upper airway obstruction, the patient had a (_______ low; _______ high) ventilation-perfusion in both lungs.

2. The patient's fatigue and respiratory rate of 6 breaths/min further caused the ventilation-perfusion ratio to (_______ rise; _______ fall).

3. As a result of the upper airway obstruction and subsequent ventilation-perfusion ratio, the parameters listed below change as follows:

   A. $P_{A_{O_2}}$: _______ increased; _______ decreased; _______ remained the same

   B. $P_{A_{CO_2}}$: _______ increased; _______ decreased; _______ remained the same

   C. $P_{C_{O_2}}$: _______ increased; _______ decreased; _______ remained the same

   D. $P_{C_{CO_2}}$: _______ increased; _______ decreased; _______ remained the same

   E. pH: _______ increased; _______ decreased; _______ remained the same

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CHAPTER 9

Control of Ventilation

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the function of the respiratory neurons of the medullary respiratory centers.
2. Describe the influence of the pontine respiratory centers on the medullary respiratory centers.
3. Describe the major areas of the body that influence breathing.
4. Describe important factors that influence breathing.

Introduction

The intrinsic rhythmicity of respiration is primarily controlled by specific neural areas located in the reticular substance of the medulla oblongata and pons of the brain. These neural areas possess monitoring, stimulating, and inhibiting properties that continually adjust the ventilatory patterns to meet specific metabolic needs. Also received and coordinated in these respiratory neural areas are the signals transmitted by the cerebral cortex during a variety of ventilatory maneuvers such as talking, singing, sniffing, coughing, or blowing into a woodwind instrument.

To fully understand the control of respiration, a basic knowledge of (1) the medullary respiratory centers, (2) the pontine respiratory centers and their influence on the medullary respiratory centers, and (3) factors that influence the rate and depth of breathing is necessary.

Control of Respiration

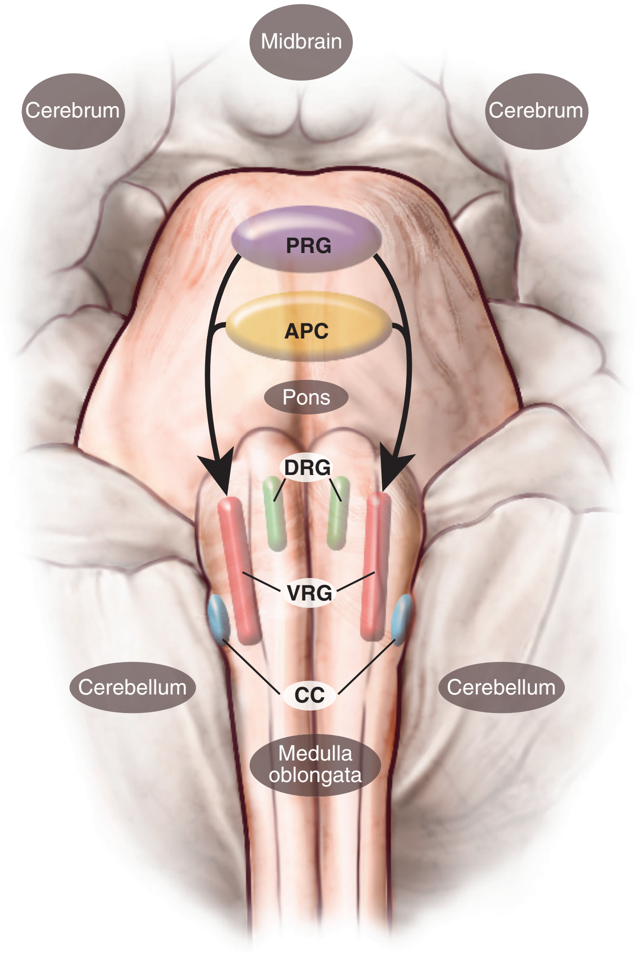
Medullary Respiratory Centers

Although knowledge concerning this subject is incomplete, it is believed that two groups of interconnected respiratory neurons, located in the medulla oblongata, are responsible for coordinating the rhythmicity of respirations. These are the **dorsal respiratory groups** and the **ventral respiratory groups** (Figure 9–1). Collectively, these respiratory neurons are referred to as the **medullary respiratory centers**.

Dorsal Respiratory Groups

The **dorsal respiratory groups (DRGs)** are located dorsally in the posterior region of the medulla oblongata near the root of cranial nerve IX. As mentioned earlier, it was once thought that the DRG neurons functioned as the primary inspiratory center—a task now known to be mainly performed by the VRGs. It is now known that the DRGs assimilate the various factors that influence breathing—for example, peripheral stretch receptors in the lungs, central chemoreceptors, and peripheral chemoreceptors (which will be described later

FIGURE 9–1 Schematic of the respiratory components of the lower brainstem (pons and medulla oblongata). Pontine respiratory centers: PRG = pontine respiratory group; APC = apneustic center; DRG = dorsal respiratory group; VRG = ventral respiratory group; CC = central chemoreceptors.



in this chapter)—and relays this information to the VRGs. The VRGs, in turn, determine the rate, depth, and rhythm of breathing.

Ventral Respiratory Groups

The **ventral respiratory groups (VRGs)** are located bilaterally in two different areas of the medulla (see Figure 9–1). The VRGs consist of a complex network of neurons that run between the ventral brain stem of the spinal cord to the pons-medulla junction. The VRGs contain specialized neurons that fire during inspiration and another set of neurons that fire during expiration. When the inspiratory neurons are stimulated, a burst of electrical impulses travels along the phrenic nerve and the intercostal nerves—causing the diaphragm and external intercostal muscles to respectively contract. This action, in turn, causes the thorax to expand and air flows into the lungs. When the VRGs' expiratory neurons fire, the inspiratory muscles relax, the lungs recoil, and expiration occurs passively. This inspiratory/expiratory cycle repeats continuously and produces a respiratory rate of about 12 to 15 breaths/min.

Until recently, it was thought that the dorsal respiratory group neurons were primarily responsible for activating inspiration. It now appears, however, that not only are the VRG neurons responsible for triggering inspiration, but they also work to coordinate the rate, depth, and rhythm of breathing. In addition, it is now believed that the VRGs generate the gasping breaths commonly seen during periods of severe hypoxia—speculated by some to be the body's last-ditch effort to restore oxygen to the brain. Breathing completely stops when certain VRG neurons are suppressed—for example, by an overdose of morphine or alcohol.

Pontine Respiratory Centers and Their Influence on Medullary Respiratory Centers

The **pontine respiratory centers**, located in the pons, consist of two specialized group of neurons known as the **pontine respiratory group (PRG)**—formally called the *pneumotaxic center*—and the **apneustic center** (see Figure 9-1). Although these unique neural areas are known to exist and can be made to operate under experimental conditions, their functional significance in humans is still not fully understood. It appears that the pontine respiratory centers function to some degree to modify and fine-tune the rhythmicity of breathing coordinated by the VRGs. For example, the neurons associated with the PRG are known to help smooth out the transition from inspiration and expiration—and the transition from expiration to inspiration. When the apneustic center is disrupted—for example, by a lesion—a prolonged or gasping type of inspiration occurs. This "breath-holding-like" phenomenon is called **apneustic breathing**. Under normal conditions, however, the apneustic center receives several different inhibitory signals, such as the lung inflation reflex (called the Hering–Breuer reflex), that suppress its function—thus, permitting expiration to occur.

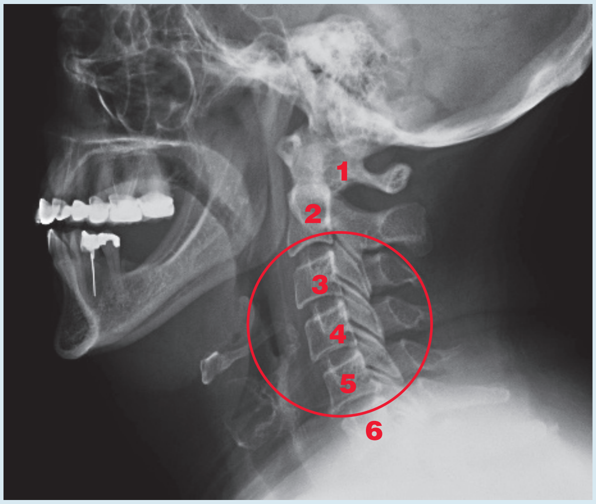
Clinical Connection 9-1

Spinal Cord Trauma and Diaphragmatic Paralysis

Injury to the cervical (neck) area can have a profound effect on the patient's ability to move and breathe. The phrenic nerve for each hemidiaphragm emerges from the spinal cord at level C3 through C5 (Figure 9–2). Depending on the degree of involvement, injury to this region of the neck can damage the phrenic nerve and cause an *incomplete* or *complete* diaphragmatic paralysis. In addition, cervical neck injuries usually result in partial or full paralysis of the patient's legs and arms (quadriplegia). However, depending on the specific location and severity of the neck trauma, limited function may be retained.

Causes of phrenic nerve injuries include blunt trauma to the neck, brainstem stroke, and spinal cord tumor. Although most patients with an incomplete injury between C3 and C5 require mechanical ventilation, the majority of the cases can eventually be weaned successfully off the ventilator. On the other hand, a complete injury above the C3 and C5 level, without mechanical ventilation, results in complete limb and diaphragmatic paralysis, ventilatory failure, and death. In these cases, the respiratory therapist has an important role in managing the patient's overall ventilatory and bronchial hygiene care.

FIGURE 9-2 The phrenic nerve for each hemidiaphragm emerges from the spinal cord at level C3 through C5. Depending on the degree of involvement, injury to this region of the neck can damage the phrenic nerve and cause an incomplete or complete diaphragmatic paralysis.



Courtesy T. Des Jardins, WindMist LLC

Factors That Influence the Rate and Depth of Breathing

From moment to moment, the medullary respiratory centers (VRG and DRG) activate specific ventilatory patterns based on information received from several areas throughout the body. The major known areas are the **central chemoreceptors** and the **peripheral chemoreceptors**. Other important factors that influence breathing originate from the (1) **Hering–Breuer reflex**, (2) **deflation reflex**, (3) **irritant reflex**, (4) **juxtapulmonary-capillary receptors**, (5) **peripheral proprioceptor reflexes**, (6) **hypothalamic controls**, (7) **cortical controls**, and (8) **aortic and carotid sinus baroreceptor reflexes**.

Central Chemoreceptors

The most powerful stimulus known to influence the medullary respiratory centers is an excess concentration of hydrogen ions [H^+] in the cerebrospinal fluid (CSF). The **central chemoreceptors**, which are located bilaterally and ventrally in the substance of the medulla, are responsible for monitoring the H^+ ion concentration of the CSF. In fact, a portion of the central chemoreceptors is actually in direct contact with the CSF. It is believed that the central chemoreceptors transmit signals to the respiratory components of the medulla by the following mechanism:

1. As the CO_2 level increases in the arterial blood (e.g., during hypoventilation), the CO_2 molecules diffuse across a semipermeable membrane, called the **blood–brain barrier**, which separates the blood from the CSF. The blood–brain barrier is very permeable to CO_2 molecules but relatively impermeable to H^+ and HCO_3^- ions.
2. As CO_2 moves into the CSF, it forms carbonic acid by means of the following reaction:

   $$CO_2 + H_2O \leftrightarrows H_2CO_3 \leftrightarrows H^+ + HCO_3^-$$

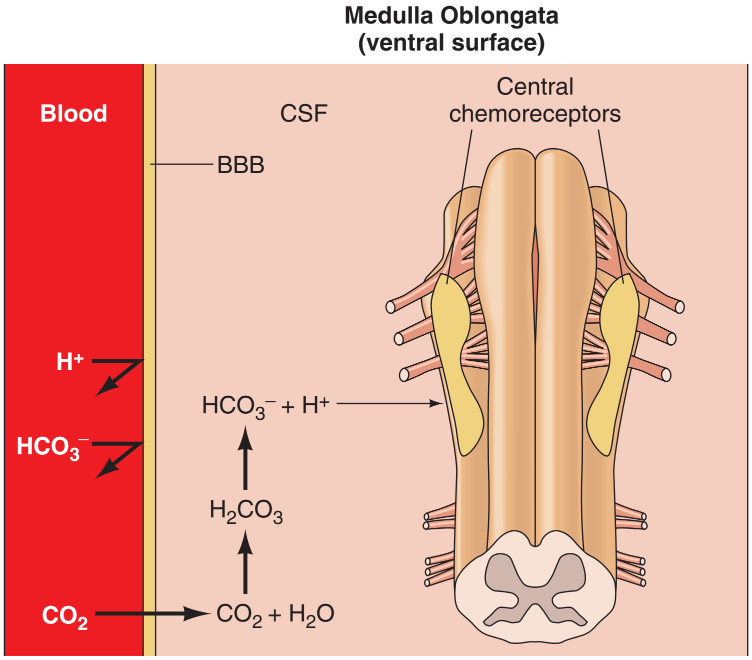
3. Because the CSF lacks hemoglobin and carbonic anhydrase and has a relatively low bicarbonate and protein level, the overall buffering system in the CSF is very slow. Because of the inefficient CSF buffering system, the H^+ generated from the preceding reaction rapidly increases and, therefore, significantly reduces the pH in the CSF.
4. The liberated H^+ ions cause the central chemoreceptors to transmit signals to the respiratory component in the medulla, which in turn increases the alveolar ventilation.
5. The increased ventilation reduces the Pa_{CO_2} and, subsequently, the P_{CO_2} in the CSF. As the P_{CO_2} in the CSF decreases, the H^+ ion concentration of the CSF also falls. This action decreases the stimulation of the central chemoreceptors. Thus, the neural signals to the respiratory components in the medulla also diminish; this in turn causes alveolar ventilation to decrease.
6. In view of the preceding sequences, it should be understood that the central chemoreceptors regulate ventilation through the indirect effects of CO_2 on the pH of the CSF (Figure 9–3).

Peripheral Chemoreceptors

The **peripheral chemoreceptors** are special oxygen-sensitive cells that react to the reductions of oxygen levels in the arterial blood. They are located high in the neck at the bifurcation of the internal and external carotid arteries and on the aortic arch (Figure 9–4). They are close to, but distinct from, the *baroreceptors*. The peripheral chemoreceptors are also called the *carotid* and *aortic bodies.*

The carotid and aortic bodies are composed of epithelial-like cells and neuron terminals in intimate contact with the arterial blood. When activated by a low Pa_{O_2}, *afferent* (sensory) signals are transmitted

FIGURE 9-3 The relationship of the blood–brain barrier (BBB) to CO_2, HCO_3^-, and H^+. CO_2 readily crosses the BBB. H^+ and HCO_3^- do not readily cross the BBB. H^+ and HCO_3^- require the active transport system to cross the BBB. CSF = cerebrospinal fluid.



to the respiratory components in the medulla by way of the glossopharyngeal nerve (ninth cranial nerve) from the carotid bodies and by way of the vagus nerve (tenth cranial nerve) from the aortic bodies. This action, in turn, causes *efferent* (motor) signals to be transmitted to the respiratory muscles, causing ventilation to increase (Figure 9–5). Compared with the aortic bodies, the carotid bodies play a much greater role in initiating an increased ventilatory rate in response to reduced arterial oxygen levels.

As shown in Figure 9–6, the peripheral chemoreceptors are not significantly activated until the oxygen content of the inspired air is low enough to reduce the Pa_{O_2} to 60 mm Hg (Sa_{O_2} about 90 percent). Beyond this point, any further reduction in the Pa_{O_2} causes a marked increase in ventilation. *Suppression* of the peripheral chemoreceptors is seen, however, when the Pa_{O_2} falls below 30 mm Hg.

In the patient with a low Pa_{O_2} and a chronically high Pa_{CO_2} level (e.g., end-stage emphysema), the peripheral chemoreceptors may be totally responsible for the control of ventilation. This is because a chronically high CO_2 concentration in the CSF inactivates the H^+ sensitivity of the central chemoreceptor—that is, HCO_3^- moves into the CSF via the active transport mechanism and combines with H^+, thus returning the pH to normal. A compensatory response to a chronically high CO_2 concentration, however, is the enhancement of the sensitivity of the peripheral chemoreceptors at higher CO_2 levels (Figure 9–7).

Finally, it is important to understand that the peripheral chemoreceptors are specifically sensitive to the P_{O_2} of the blood and relatively insensitive to the oxygen content of the blood. The precise mechanism for this exclusive P_{O_2} sensitivity is not fully understood.

Clinically, this exclusive Pa_{O_2} sensitivity can be misleading. For example, there are certain conditions in which the Pa_{O_2} is normal (and, therefore, the peripheral chemoreceptors are not stimulated), yet the oxygen content of the blood is dangerously low. Such conditions include chronic anemia, carbon monoxide poisoning, and methemoglobinemia.

FIGURE 9-4 Location of the carotid and aortic bodies (the peripheral chemoreceptors).

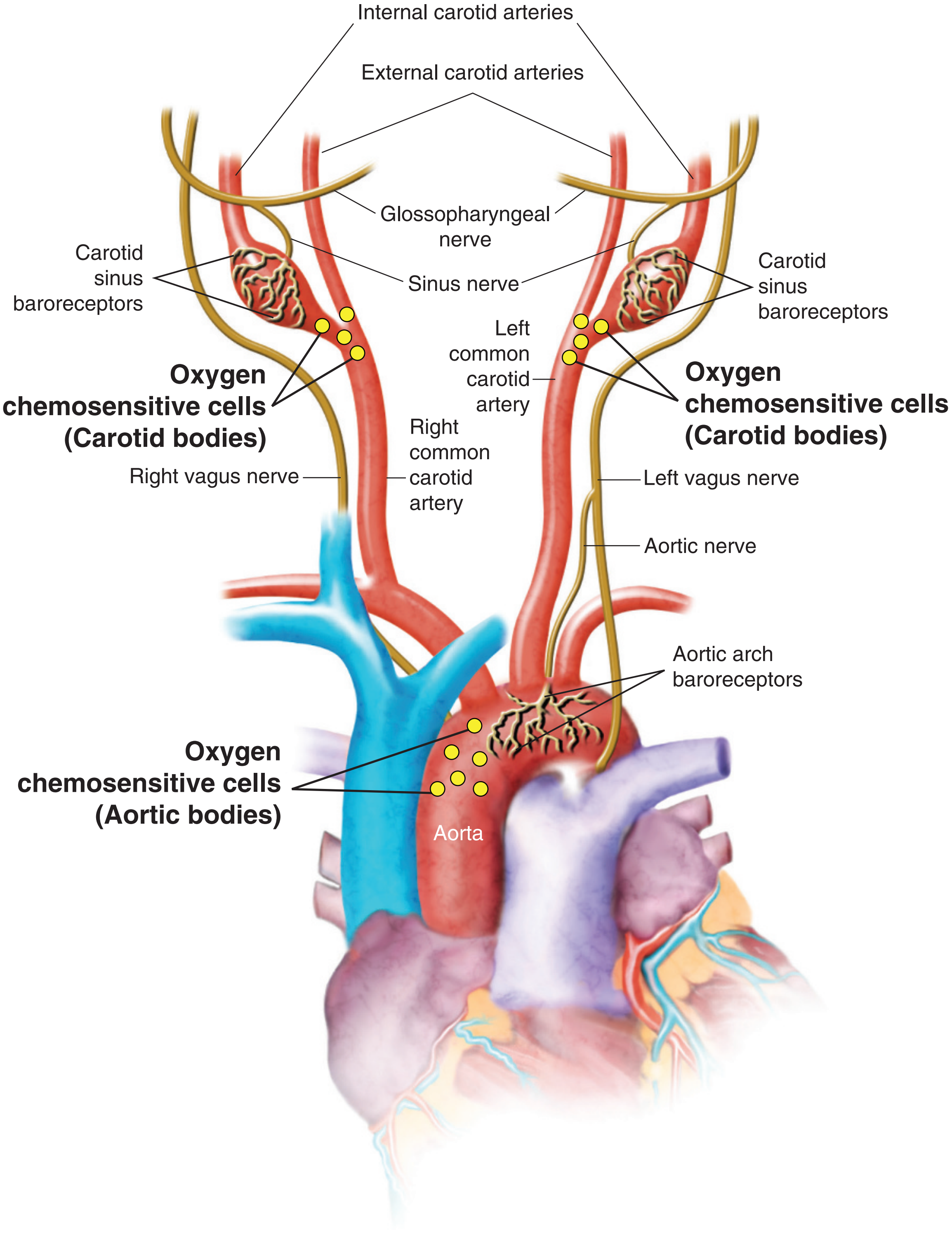

Internal carotid arteries
External carotid arteries
Glossopharyngeal nerve
Carotid sinus baroreceptors
Sinus nerve
Carotid sinus baroreceptors
Left common carotid artery
Oxygen chemosensitive cells (Carotid bodies)
Oxygen chemosensitive cells (Carotid bodies)
Right common carotid artery
Right vagus nerve
Left vagus nerve
Aortic nerve
Aortic arch baroreceptors
Oxygen chemosensitive cells (Aortic bodies)
Aorta

FIGURE 9-5 Schematic showing how a low Pa_{O_2} stimulates the respiratory components of the medulla to increase alveolar ventilation.

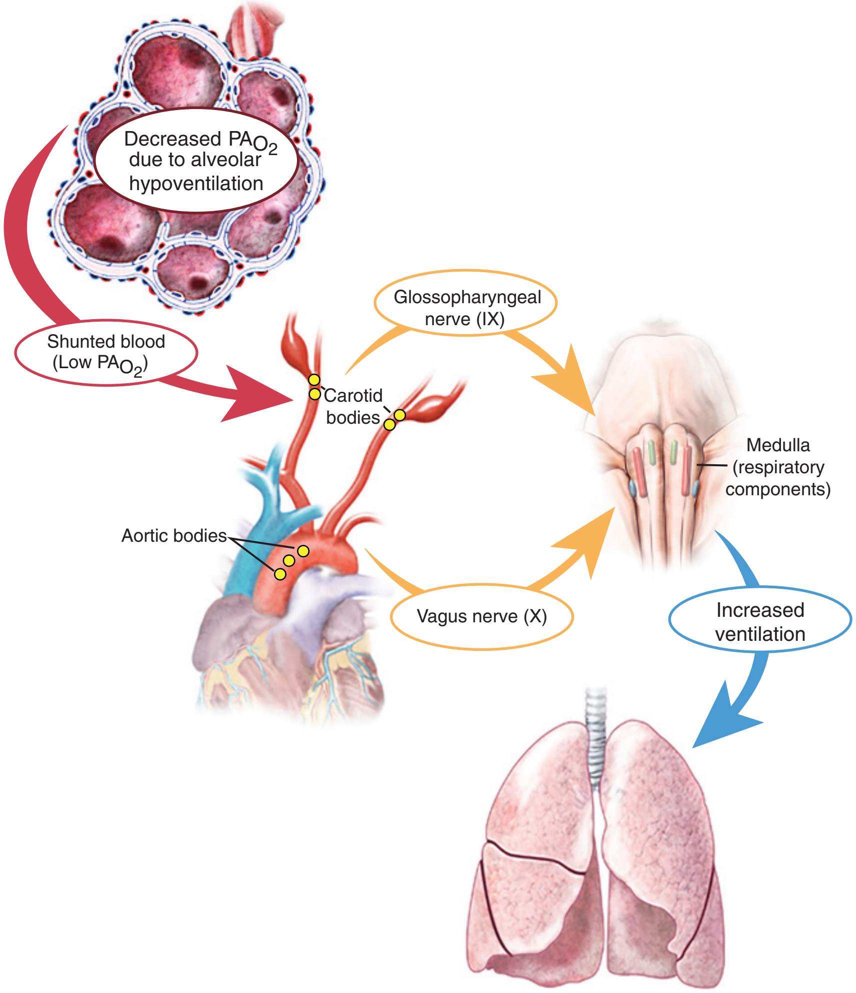

Decreased PA_{O_2} due to alveolar hypoventilation
Shunted blood (Low PA_{O_2})
Carotid bodies
Glossopharyngeal nerve (IX)
Medulla (respiratory components)
Aortic bodies
Vagus nerve (X)
Increased ventilation

FIGURE 9-6 The effect of low Pa_{O_2} levels on ventilation.

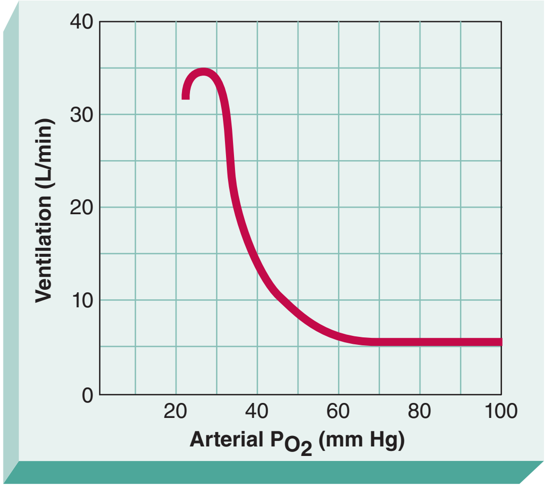
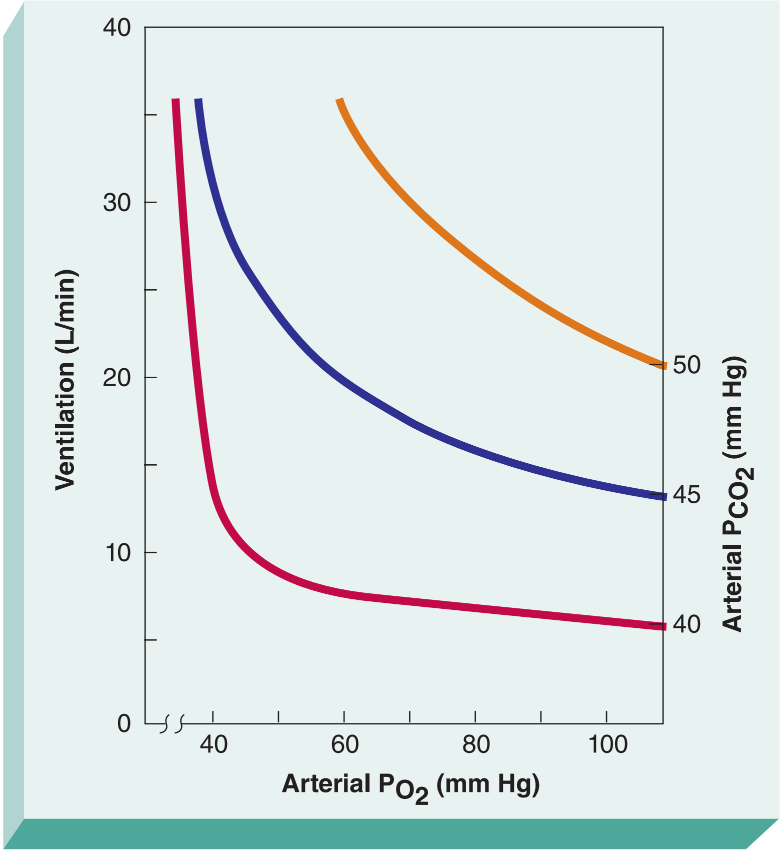


FIGURE 9-7 The effect of Pa_{O_2} on ventilation at three different Pa_{CO_2} values. Note that as the Pa_{CO_2} value increases, the sensitivity of the peripheral chemoreceptors increases.



Clinical Connection 9-2

Altitude Changes—The Role of the Peripheral Chemoreceptors and Central Chemoreceptors in the Stimulation of Ventilation

In the Clinical Application Case 1 (page 382), the reader is provided with an overview of (1) why the respiratory rate is increased to a new baseline level when an individual, who normally resides at sea level, ascends to a high altitude for 2 weeks, and (2) why the respiratory rate continues to be higher than normal when the individual returns back to sea level. The following areas are discussed:

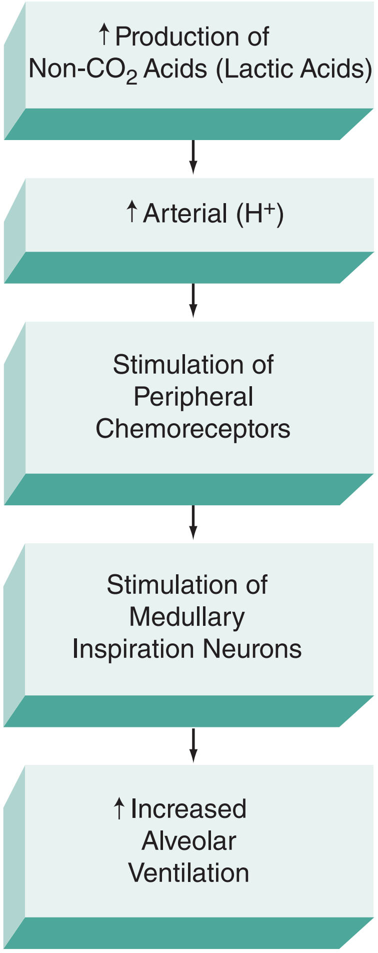
- How the oxygen peripheral chemoreceptors play an important—and overriding—role in stimulating an increased ventilator rate at high altitudes.
- How the increased respiratory rate at a high altitude indirectly recalibrates the sensitivity of central chemoreceptors—to a lower Pa_{CO_2} (H^+) baseline level—during a 2-week period.
- How the central chemoreceptors continue to keep the respiratory rate higher than normal after the individual returns to sea level.

Other Factors That Stimulate the Peripheral Chemoreceptors

Although the peripheral chemoreceptors are primarily stimulated by a reduced Pa_{O_2} level, they are also activated by a decreased pH (increased H^+ level). This is an important feature of the peripheral chemoreceptors because there are many situations in which a change in arterial H^+ ion levels can occur by means other than a primary change in the Pa_{O_2}. In fact, because the H^+ ions do not readily move across the blood–brain barrier, the peripheral chemoreceptors play a major role in initiating ventilation whenever the H^+ ion concentration increases for reasons other than an increased Pa_{CO_2}. For example, the accumulation of lactic acid or ketones in the blood stimulates hyperventilation almost entirely through the peripheral chemoreceptors (Figure 9–8).

The peripheral chemoreceptors are also stimulated by (1) hypoperfusion (e.g., stagnant hypoxia), (2) increased temperature, (3) nicotine, and (4) the direct effect of Pa_{CO_2}. The response of the peripheral chemoreceptors to Pa_{CO_2} stimulation, however, is minor and not nearly so great as the response generated by the central chemoreceptors. The peripheral chemoreceptors do respond faster than the central chemoreceptors to an increased Pa_{CO_2}. This occurs because the peripheral chemoreceptors are stimulated directly by the CO_2 molecule, whereas the central chemoreceptors are stimulated by the H^+ generated by the CO_2 hydration reaction in the CSF—a reaction that occurs slowly in the absence of carbonic anhydrase (see Figure 9–3).

FIGURE 9-8 The accumulation of lactic acids leads to an increased alveolar ventilation primarily through the stimulation of the peripheral chemoreceptors.


↑ Production of Non-CO2 Acids (Lactic Acids)
↑ Arterial (H+)
Stimulation of Peripheral Chemoreceptors
Stimulation of Medullary Inspiration Neurons
↑ Increased Alveolar Ventilation

Other Responses Activated by the Peripheral Chemoreceptors

In addition to the increased ventilation activated by the peripheral chemoreceptors, other responses can occur as a result of peripheral chemoreceptor stimulation, including:

- Peripheral vasoconstriction
- Increased pulmonary vascular resistance
- Systemic arterial hypertension
- Tachycardia
- Increase in left ventricular performance

Clinical Connection 9-3

Hydrogen Ion (H^+) Accumulation and Its Role in Stimulating the Peripheral Chemoreceptors

In the Clinical Application Case 2 (page 383), the respiratory therapist is called to assist in the care of a 44-year-old female unconscious as a result of a diabetic crisis. This case illustrates how clinical factors other than a decreased Pa_{O_2} can stimulate the oxygen peripheral chemoreceptors. Because the patient had not taken her insulin as prescribed, ketone acids had accumulated and caused the pH to fall. The excessive H^+ level stimulated the peripheral chemoreceptors and caused the patient's respiratory rate to increase. This case nicely shows (1) how the peripheral chemoreceptors can be stimulated by an excessive H^+ concentration, (2) how this action caused an increase in the patient's respiratory rate, and (3) how the increased respiratory rate compensated for a low pH level by decreasing the Pa_{CO_2} level—another source of H^+.

Clinical Connection 9-4

Hazards of Oxygen Therapy in Patients with Chronic Hypercapnia and Hypoxemia

In some patients with chronic hypercapnia (chronically higher than normal Pa_{CO_2} levels) and hypoxemia (e.g., COPD), the administration of too much oxygen may suppress the peripheral oxygen chemoreceptors and depress ventilation. In other words, too much oxygen may cause acute ventilatory failure (acute respiratory acidosis) superimposed on the chronic ventilatory failure (compensated respiratory acidosis).

Clinically, oxygen-induced hypoventilation is commonly observed in the relaxed, unstimulated patient with chronic hypercapnia. Patients who are experiencing oxygen-induced hypoventilation are often described as sleepy, lethargic, and difficult to arouse, with slow and shallow breathing.

Although the precise mechanism responsible for this phenomenon is not known and continues to be the subject of much controversy and debate, the respiratory therapist must know that caution needs to be taken not to over-oxygenate patients with chronic ventilatory failure with hypoxemia (compensated respiratory acidosis).

Other Important Factors That Influence Breathing

Hering–Breuer Reflex

The **Hering–Breuer reflex** (also called the *inflation reflex*) is generated by stretch receptors, located in the visceral pleurae and in the walls of the bronchi and bronchioles, that become excited when the lungs overinflate. Signals from these receptors travel through the afferent fibers of the vagus nerve to the respiratory components in the medulla, causing inspiration to cease. In essence, the lungs themselves provide a feedback mechanism to terminate inspiration. Instead of a reflex to control ventilation, the Hering–Breuer reflex appears to be a protective mechanism that prevents pulmonary damage caused by excessive lung inflation. The significance of the Hering–Breuer reflex in the adult at normal tidal volumes is controversial; it appears to have more significance in the control of ventilation in the newborn.

Deflation Reflex

When the lungs are compressed or deflated, an increased rate of breathing results. The precise mechanism responsible for this reflex is not known. Some researchers believe that the increased rate of breathing may be due to the reduced stimulation of receptors serving the Hering–Breuer reflex rather than to the stimulation of specific deflation receptors. Others, however, think that the deflation reflex is not due to the absence of receptor stimulation of the Hering–Breuer reflex, because the reflex is still seen when the temperature of the bronchi and bronchioles is less than 8°C. The Hering–Breuer reflex is not active when the bronchi and bronchioles are below this temperature.

Irritant Reflex

When the lungs are exposed to noxious gases or accumulated mucus, the irritant receptors may also be stimulated. The irritant receptors are subepithelial mechanoreceptors located in the trachea, bronchi, and bronchioles. When the receptors are activated, a reflex vagal response causes the ventilatory rate to increase. Stimulation of the irritant receptors may also produce a reflex cough, sneeze, and bronchoconstriction.

Juxtapulmonary-Capillary Receptors

An extensive network of free nerve endings, called **C-fibers**, are located in the small conducting airways, blood vessels, and interstitial tissues between the pulmonary capillaries and alveolar walls. The C-fibers located near the alveolar capillaries are called **juxtapulmonary-capillary receptors**, or **J-receptors**. These receptors react to certain chemicals and to mechanical stimulation. For example, they are stimulated by alveolar inflammation, pulmonary capillary congestion and edema, humoral agents (e.g., serotonin, bradykinin), lung deflation, and emboli. When J-receptors are stimulated, a reflex response triggers a rapid, shallow breathing pattern.

Peripheral Proprioceptor Reflexes

Peripheral proprioceptors are located in the muscles, tendons, joints, and pain receptors in muscles and skin. When stimulated, the proprioceptors send neural impulses to the medulla. The medulla, in turn, sends out an increased number of inspiratory signals. This may explain, in part, why moving an individual's limbs (e.g., during a drug overdose), or producing prolonged pain to the skin, stimulates ventilation. Sudden pain causes a short period of apnea, whereas prolonged pain causes the breathing rate to increase. The proprioceptors in the joints and tendons are also believed to play an important role in initiating and maintaining an increased respiratory rate during exercise. The more joints and tendons are involved, the greater the respiration rate.

Hypothalamic Controls

Strong emotions can activate sympathetic centers in the hypothalamus, which can alter respirations. For example, excitement causes the respiratory rate to increase. In addition, increased body temperature causes the respiration rate to increase, whereas decreased body temperature produces the opposite effect. For instance, a sudden cold stimulus (e.g., plunging into very cold water) can cause the cessation of breathing—or at the very least, a gasp.

Cortical Controls

Although the breathing pattern is normally controlled involuntarily by the medullary centers, one can also activate a conscious voluntary control over the rate and depth of breathing—or choose to hold the breath or take an extra deep breath.

Aortic and Carotid Sinus Baroreceptor Reflexes

The normal function of the aortic and carotid sinus baroreceptors, located near the aortic and carotid peripheral chemoreceptors (refer to Figure 5–19), is to initiate reflexes that cause a decreased heart and ventilatory rate in response to an elevated systemic blood pressure and an increased heart and ventilatory rate in response to a reduced systemic blood pressure.

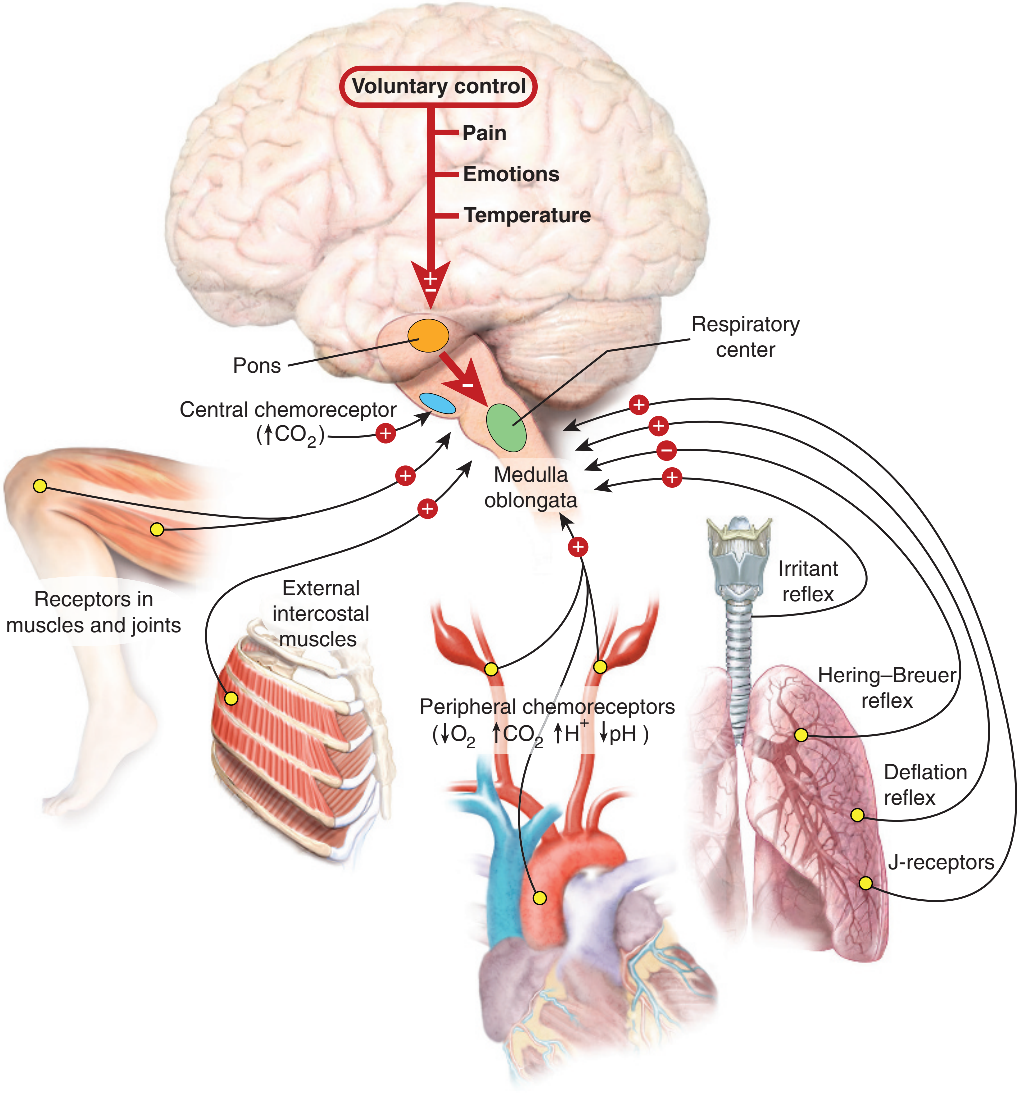
To summarize, the *respiratory center* of the medulla oblongata coordinates both the involuntary and voluntary rhythm of breathing. The respiratory center (1) receives neural impulses from several different areas throughout the body, (2) evaluates and prioritizes these neural signals, and (3) based on the metabolic needs of the body, elicits neural impulses to the muscles of ventilation. Figure 9–9 provides an overview of the complex functions of the medulla.

Miscellaneous Factors That May Influence Breathing

Finally, there are a number of known miscellaneous factors that may also influence breathing, including the following sensory impulses from thermal receptors on the skin and from superficial or deep pain receptors:

- **Pain.** A sudden painful stimulation causes a reflex apnea. However, a prolonged painful stimulus causes faster and deeper breathing.
- **Sudden cold stimulation.** A sudden cold stimuli—such as a plunge into cold water—causes a reflex apnea.
- **Stimulation of the pharynx or larynx.** The stimulation of the pharynx or larynx by irritating chemicals or tactile stimulation causes a temporary apnea. This also includes the choking reflex, which is a valuable protective mechanism to prevent aspiration of food or liquids during swallowing.

FIGURE 9-9 The respiratory center coordinates signals from the higher brain region, great vessels, airways, lungs, and chest wall. (+) = increased ventilatory rate; (−) = decreased ventilatory rate.


Voluntary control
Pain
Emotions
Temperature
+
Respiratory center
Pons
−
Central chemoreceptor
(↑CO_2)
+
Medulla oblongata
+
+
+
+
−
+
+
Receptors in muscles and joints
External intercostal muscles
Irritant reflex
Hering–Breuer reflex
Peripheral chemoreceptors
(↓O_2 ↑CO_2 ↑H^+ ↓pH)
Deflation reflex
J-receptors

Clinical Connection 9-5

Unusual Breathing Reflexes

Cough Reflex. Foreign matter in the trachea or large bronchi activates a cough reflex. The epiglottis and glottis reflexively close, and the expiratory muscles contract, causing the air pressure in the lungs to increase. This is followed by the sudden opening of the epiglottis and glottis, which results in an upward burst of gas that eliminates the offending foreign substance—the cough.

Sneeze Reflex. Similar to the cough reflex, a sneeze reflex is a forceful involuntary expulsion of air through the nose and mouth caused by an irritation to the mucous membranes of the nasal passageways.

(*Continued*)

Clinical Connection 9-5, Continued

A sudden burst of air moves through the nose and mouth and forces the irritating substances (and mucus) out of the upper airway. It is estimated that the droplets from a sneeze can travel more than 100 miles per hour and travel up to 12 feet. What is called a **photo sneeze reflex** (also called a photic sneeze response, sun sneezing, and photogenic sneezing) is thought to be a genetic autosomal dominant trait, which is activated when an individual is suddenly exposed to bright light (Figure 9–10).

Hiccup. A hiccup is a characteristic sound that is generated by an involuntary contraction of the diaphragm, followed by the sudden closure of the glottis. Causes of hiccups include eating too much, drinking carbonated beverages, excessive consumption of alcohol, sudden temperature changes, and excitement or emotional stress. Although most episodes of hiccups do not last longer than a few minutes, recurrent and prolonged hiccup attacks sometimes occur. This problem is most often seen in men. Sedatives may be used in severe cases.

Yawn. A yawn is an involuntary act of opening the mouth wide and inhaling deeply. A yawn tends to occur when an individual is sleepy, drowsy, bored, or depressed. Yawning may be accompanied with upper body movements or the act of stretching to enhance chest expansion. Humans are not alone in the act of yawning. Dogs, cats, snakes, and even fish yawn. In spite of an extensive amount of research, the cause of yawning is not known. However, it is know that yawning is an involuntary movement that makes an individual's mouth open wide and breathe deeply. As the jaw drops, air flows into the lungs and the diaphragm moves downward. At the peak of the yawn, the lungs are stretched to capacity and the heart rate increases. Although many physiological aspects of a yawn have been well documented, researchers still cannot answer this fundamental question—Why do we yawn?

One common theory suggests that yawning serves to draw in more oxygen and to remove carbon dioxide. However, some researchers have tested this theory and found that administering oxygen to test subjects or decreasing their carbon dioxide did not prevent yawning. Some researchers suggest that yawning is contagious. Although this has not been scientifically confirmed, it is a good wager that a large number of students have had the inspiration to yawn after reading this clinical connection—correct?

Mammalian Diving Reflex. A fascinating, but poorly understood, physiological response called the *mammalian diving reflex* has been identified as the mechanism responsible for a number of remarkable recoveries of apparent cold water drowning victims—including some who have been submerged for more than 40 minutes! Even though drowning victims initially appear dead when pulled out of the cold water—that is, their breathing has stopped, their pupils are fixed and dilated, they appear cyanotic, and they have no pulse—cardiopulmonary resuscitation efforts are successful.

We do know that the diving reflex enhances breath holding in cold water. We also know that

FIGURE 9-10 Sneeze.

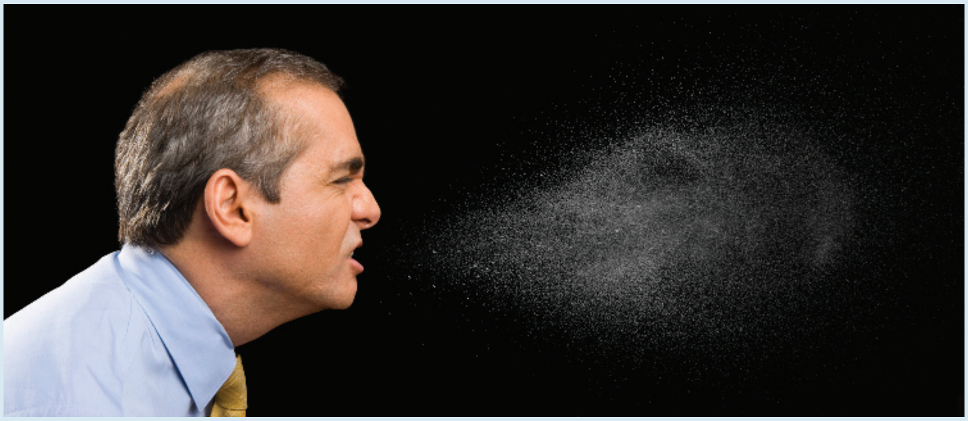


Photo courtesy CDC/James Gathany

Clinical Connection 9-5, Continued

the diving reflex is an adaptation mechanism found in marine mammals (e.g., seals, otters, dolphins)—and, to a lesser extent, in humans. For example, the Weddell seals of Antarctica can hold their breath for up to 1 hour and can dive to depths of 500 meters. Although the diving reflex is weaker in human, it is known that when cold water—less than 20°C (68°F)—contacts the face or inside the nose, sensory neurons are stimulated that increase parasympathetic activity. The cold-water stimulation stops breathing, slows the heart rate, slows metabolism (decreasing oxygen and nutrient needs), and causes peripheral vasoconstriction—shunting blood to vital organs. The diving reflex is not observed during normal breath holding in air or during simulated dives in warm water. Apparently, the colder the water and the younger the victim, the better the chance of survival.

Clinical Connection 9-6

Second Wind

Second wind is a phenomenon associated with prolonged exercise—such as long-distance marathon running and bike racing—whereby the individual has a sudden transition from an ill-defined feeling of fatigue and shortness of breath to a more comfortable, less stressful feeling during the athletic event—oftentimes, with the strength to press on at—or greater than—their top performance. Today, the phrase "second wind" is commonly used as a metaphor for continuing on with renewed energy beyond the point of an individual's top performance—whether in other sports, a career or job performance, or life activities in general. Although the precise mechanism is still under debate, the stimulus for a second wind is thought to be associated with the following:

- **Lactic acid.** When individuals exercise for a long period of time, and push past the point of pain and exhaustion, they may give their systemic vascular system enough time—that is, a warmup period—to find the correct balance between the supply of oxygen and the tissue cell metabolism, thereby offsetting the buildup of lactic acid in the muscles.
- **Endorphins.** Endorphins are naturally occurring pain-reducing substances that are secreted by the anterior portion of the pituitary gland during stress and trauma. Endorphins act on certain parts of the brain to elicit a euphoria feeling, or what is commonly referred to as a "natural high."
- **Psychological.** The second wind may also be associated with a psychological factor—a by-product of the confidence and pride an individual may experience by exceeding his or her supposed limitation.

Chapter Summary

The respiratory neurons of the medulla oblongata coordinate both the involuntary and voluntary rhythm of breathing. The medullary *respiratory center* of the medulla receives neural impulses from several different areas throughout the body, evaluates and prioritizes the signals, and elicits neural impulses to the muscles of ventilation based on the metabolic need of the body.

To fully understand this subject, the respiratory therapist must have a basic knowledge of (1) the respiratory components of the medulla, including the ventral respiratory groups (VRGs) and the dorsal respiratory groups (DRGs); (2) the pontine respiratory centers and their influence on the medullary respiratory centers; and (3) the factors that influence the rate and depth of breathing—including the central chemoreceptors, peripheral chemoreceptors, Hering–Breuer reflex, deflation reflex, irritant reflex, juxtapulmonary-capillary receptors, peripheral proprioceptor reflexes, hypothalamic controls, cortical controls, and the aortic and carotid sinus baroreceptor reflexes. Miscellaneous factors that may also influence breathing include sudden and prolonged pain, sudden cold stimulation, and stimulation of the pharynx and larynx.

Clinical connections associated with these topics include (1) spinal cord trauma and diaphragmatic paralysis, (2) altitude changes and the role of the peripheral chemoreceptors and central chemoreceptors in the stimulation of ventilation, (3) hydrogen ion (H^+) accumulation and its role in stimulating the peripheral chemoreceptors, (4) the hazards of oxygen therapy in patients with chronic hypercapnia and hypoxemia, (5) unusual breathing reflexes, and (6) second wind.

1 Clinical Application Case

To facilitate the understanding of how the peripheral and central chemoreceptors control the ventilatory pattern, consider the following chain of events that develops when an individual who normally resides at sea level ascends to a high altitude—say, to the Colorado mountains to ski for a period of 2 weeks (Figure 9-11).

Changes at High Altitudes

Stimulation of the Peripheral Chemoreceptors

1. As the individual ascends the mountain, the barometric pressure, and, therefore, the P_{O_2} of the atmosphere progressively decrease. (Remember that the oxygen percentage is still 21 percent.)
2. As the atmospheric P_{O_2} decreases, the individual's arterial oxygen pressure (Pa_{O_2}) also decreases.
3. As the individual continues to ascend the mountain, the Pa_{O_2} eventually falls low enough (to about 60 mm Hg) to activate the peripheral chemoreceptors to stimulate the medulla to increase ventilation.
4. The increased ventilation initiated by the peripheral chemoreceptors causes a secondary decrease in the Pa_{CO_2}. In other words, the individual hyperventilates in response to the reduced Pa_{O_2} level.
5. Because the peripheral chemoreceptors do not acclimate to a decreased oxygen concentration, hyperventilation will continue for the entire time the individual remains at the high altitude.

Readjustment of the Central Chemoreceptors

In response to the hyperventilation that occurs while the individual is at the high altitude, the central chemoreceptors readjust to the lower CO_2 level because of the following chain of events:

1. As the individual hyperventilates to offset the low atmospheric P_{O_2}, the individual's Pa_{CO_2} level decreases.
2. In response to the decreased Pa_{CO_2}, the CO_2 molecules in the CSF move into the blood until equilibrium occurs.
3. This reaction causes the pH of the CSF to increase.
4. Over the next 48 hours, however, HCO_3^- will also leave the CSF (via the active transport mechanism) to correct the pH back to normal.

In short, the individual's CSF readjusts to the low CO_2 level.

Changes after Leaving a High altitude

Stimulation of the Central Chemoreceptors

Interestingly, even after the individual returns to a lower altitude, hyperventilation continues for a few days. The reason for this is as follows:

1. As the individual moves down the mountain, the barometric pressure steadily increases, and, therefore, the atmospheric P_{O_2} increases.
2. As the atmospheric P_{O_2} increases, the individual's Pa_{O_2} also increases and eventually ceases to stimulate the peripheral chemoreceptors.
3. As the stimulation of the peripheral chemoreceptors decreases, the individual's ventilatory rate decreases.
4. As the ventilatory rate declines, however, the individual's Pa_{CO_2} progressively increases.
5. As the Pa_{CO_2} increases, CO_2 molecules move across the blood–brain barrier into the CSF.
6. As CO_2 moves into the CSF, H^+ ions are formed, causing the pH of the CSF to decrease.
7. The H^+ ions liberated in the preceding reaction stimulate the central chemoreceptors to increase the individual's ventilatory rate.
8. Eventually, HCO_3^- ions move across the blood–brain barrier into the CSF to correct the pH back to normal. When this occurs, the individual's ventilatory pattern will be as it was before the trip to the mountains.

Clinical Application Case 1 (continued)

FIGURE 9-11 Skiing at high altitudes.

2 Clinical Application Case

A 44-year-old woman was found unconscious on her living room floor by her husband when he returned home from work. He immediately carried her to his car and drove her to the hospital. As he was driving, he called the hospital emergency department on his cell phone to alert the medical staff. He estimated that his time of arrival would be about 15 minutes. While on the phone, he also reported that his wife had a long history of diabetes. He stated that his wife had passed out three times in the past 2 years as a result of not taking her insulin as prescribed. The husband had no idea how long his wife had been unconscious before he found her.

Upon arrival, the patient was still unconscious and breathing very deeply and rapidly. The emergency department nurse placed an oxygen mask on the patient's face and started an intravenous infusion. A laboratory phlebotomist drew blood, and the respiratory therapist obtained an arterial blood sample from the patient's radial artery. The patient's vital signs were blood pressure—135/85 mm Hg, heart rate—97 beats/min, respirations—22 breaths/min, and temperature—37°C. The patient's respiratory pattern was charted by the respiratory therapist as Kussmaul's respiration. The patient's arterial blood gas values were pH—7.23, Pa_{CO_2}—24 mm Hg, HCO_3^-—19 mEq/L, and Pa_{O_2}—405 mm Hg. The respiratory therapist discontinued the patient's oxygen therapy. The second set of arterial blood gas values on room air were pH—7.23, Pa_{CO_2}—24 mm Hg, HCO_3^-—19 mEq/L, and Pa_{O_2}—119 mm Hg.

The laboratory report showed a blood glucose level of 837 mg/dL (normal, 70 to 150). The report also showed that her serum acetone level was 1:64 (normal, 0). The attending physician initiated insulin therapy. Two hours later, the patient was conscious and talking with her husband. Her vital signs were blood pressure—122/68 mm Hg, heart rate—75 beats/min, respirations—12 breaths/min, and temperature—37°C. Arterial blood gas values on room air at this

(*continued*)

Clinical Application Case 2 (continued)

time were pH—7.41, Pa_{CO_2}—39 mm Hg, HCO_3^-—24 mEq/L, and Pa_{O_2}—95 mm Hg. Her blood glucose level was 95 mg/dL, and her acetone level was zero. The patient was discharged the next day.

Discussion

This case illustrates how clinical factors other than an increased Pa_{CO_2} or decreased P_{O_2} can stimulate ventilation. Because the patient had not taken her insulin as prescribed, ketone acids (H^+) started to accumulate in her blood. As the ketone acid level increased, pH decreased. The excessive H^+ concentration stimulated the patient's peripheral chemoreceptors. Because the H^+ ion does not readily move across the blood–brain barrier, the peripheral chemoreceptors played a major role in causing the patient's ventilation to increase (see Figure 9–8).

In addition, note that as the patient's ventilation increased, her Pa_{CO_2} decreased (to 24 mm Hg in the emergency department). The reduction in the Pa_{CO_2} was a compensatory mechanism—that is, the decreased Pa_{CO_2} worked to offset the acidic pH caused by the increased ketone acids. In other words, if the Pa_{CO_2} had been closer to normal level (around 40 mm Hg) in the emergency department, the pH would have been lower than 7.23.

Note also that an increased respiratory rate does not necessarily mean that patient needs oxygen therapy. In this case, however, such therapy was appropriate (because of the patient's rapid breathing) until the cause of the rapid breathing was determined. When the results of the first arterial blood gas analysis were available (Pa_{O_2} was 405 mm Hg), discontinuation of the oxygen therapy was the appropriate response.

Review Questions

1. The respiratory components of the medulla consist of which of the following?

1. Dorsal respiratory group
2. Apneustic center
3. Ventral respiratory group
4. Pneumotaxic center

A. 1 only
B. 2 only
C. 1 and 3 only
D. 2 and 4 only

2. Which of the following has the most powerful effect on the respiratory components of the medulla?

A. Decreased O_2
B. Increased H^+
C. Decreased CO_2
D. Increased pH

3. Which of the following may cause a temporary cessation in breathing?

1. Sudden pain
2. Stimulation of proprioceptor
3. Sudden cold
4. Inhalation of noxious gases

A. 1 only
B. 2 only
C. 3 and 4 only
D. 1 and 3 only

4. Which of the following will readily diffuse across the blood–brain barrier?

1. CO_2
2. H^+
3. HCO_3^-
4. H_2CO_3

A. 1 only
B. 2 only
C. 3 only
D. 2 and 4 only

5. When the systemic blood pressure increases, the aortic and carotid sinus baroreceptors initiate reflexes that cause a/an

1. Increased heart rate
2. Decreased ventilatory rate
3. Increased ventilatory rate
4. Decreased heart rate

A. 1 only
B. 2 only
C. 3 only
D. 2 and 4 only

6. The peripheral chemoreceptors are significantly activated when the P_{O_2} decreases to about

A. 75 mm Hg
B. 70 mm Hg
C. 65 mm Hg
D. 60 mm Hg

7. Stimulation of the peripheral chemoreceptors can cause which of the following?

1. Tachycardia
2. Decreased left ventricular performance
3. Increased pulmonary vascular resistance
4. Systemic arterial hypertension
   A. 1 only
   B. 2 only
   C. 4 only
   D. 1, 3, and 4 only

8. Suppression of the peripheral chemoreceptors begins when the P_{O_2} falls below

A. 50 mm Hg
B. 40 mm Hg
C. 30 mm Hg
D. 20 mm Hg

9. In addition to a low P_{O_2}, the peripheral chemoreceptors are also sensitive to a/an

1. Decreased H^+
2. Increased P_{CO_2}
3. Decreased pH
4. Increased temperature
   A. 2 only
   B. 3 only
   C. 1, 2, and 3 only
   D. 2, 3, and 4 only

10. Which of the following protects the lungs from excessive inflation?

A. Juxtapulmonary-capillary receptors
B. Hering–Breuer inflation reflex
C. Deflation reflex
D. Irritant reflex

Clinical Application Questions

Case 1

1. True ________ False ________ As an individual ascends a mountain, both the barometric pressure and atmospheric P_{O_2} decrease.

2. True ______ False ______ The oxygen percentage decreases as an individual ascends a mountain.

3. What stimulates the medulla to increase ventilation as an individual continues to ascend a mountain?

____

4. As an individual continues to hyperventilate at high altitudes, the individual's Pa_{CO_2} (________ increases; ________ decreases; ________ remains the same).

5. After an individual returns to a lower altitude, an increased ventilation continues for a few days. What causes the individual to maintain a higher than normal respiratory rate?

____

Case 2

1. Because the patient had not taken her insulin as prescribed, what type of acid accumulated in her blood?

____

2. What did the excess acid in the patient's blood stimulate that caused the patient's respiratory rate to increase?

____

3. Do H^+ ions readily move across the blood–brain barrier?

Yes ________ No ________

4. Explain why the patient's increased ventilation was a compensatory mechanism to offset the acidic pH.

____

____

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CHAPTER 10

Fetal Development and the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the developmental events that occur during the periods of fetal life.
2. Describe how the following components relate to the placenta: umbilical arteries, cotyledons, fetal vessels, chorionic villi, intervillous space, spiral arterioles, and umbilical vein.
3. List the three major reasons oxygen transfers from maternal to fetal blood.
4. List the factors believed to cause the wide variance between the maternal and fetal P_{O_2} and P_{CO_2}.
5. Describe the structures that relate to fetal circulation.
6. Describe what happens to the special structures of fetal circulation after birth.
7. Describe how fetal lung fluid is removed from the lungs at birth.
8. List the number of alveoli present at birth and at 12 years of age.
9. Describe the first breath, and include the pressure-volume changes of the lungs of the newborn during the first 2 weeks of life.
10. Identify the average newborn values for lung compliance and airway resistance.
11. Describe the circulatory changes that develop at birth.
12. Describe the role of peripheral chemoreceptors, central chemoreceptors, and infant reflexes in the control of ventilation of the newborn.
13. List the normal values in the newborn for lung volumes and capacities, heart rate, and blood pressure.

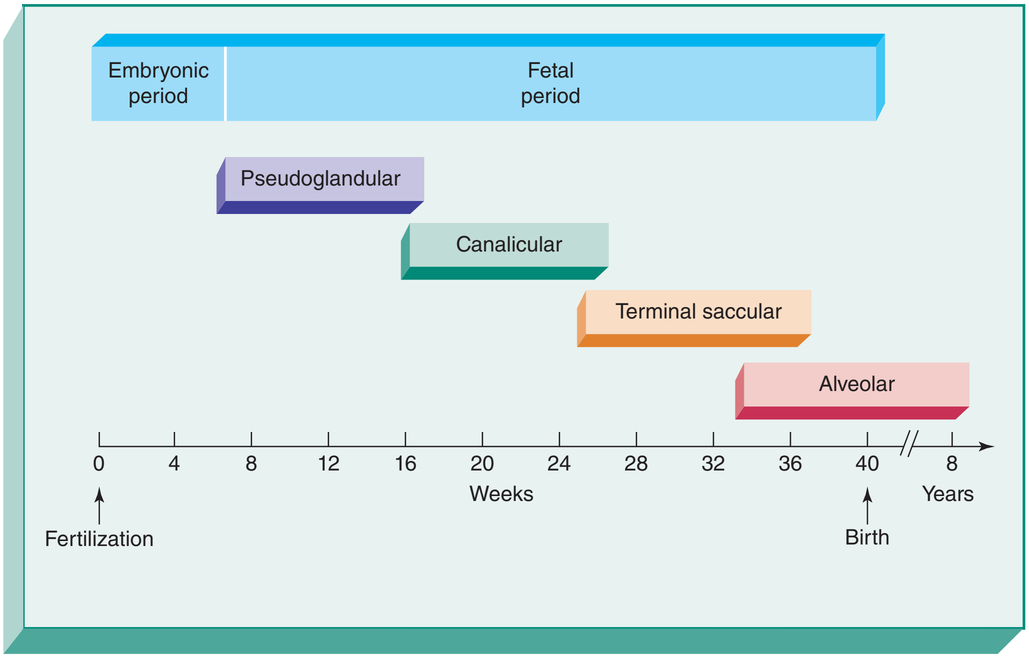
Fetal Lung Development

During fetal life, lung development occurs over the following five phases in utero: *embryonic, pseudoglandular, canalicular, terminal saccular, and alveolar period* (Figure 10–1).

Embryonic Period

The **embryonic period** begins around the 26th day after conception and continues to the 6th week of gestation. The lungs first appear as a small bud arising from the primitive esophagus (Figure 10–2). The lung bud (called the ventral respiratory diverticulum) continues to grow and divide into primitive lobar bronchi—two on the left lung bud and three on the right lung bud. By the end of the embryonic phase, the major bronchi are present—10 branches in the right lung and 9 branches in the left lung.

FIGURE 10-1 Major phases of respiratory development.



By the end of the 5th week, cartilage can be seen in the trachea, and the main stem bronchi are surrounded by primitive cellular mesoderm, which gradually differentiates into pulmonary arteries and veins, segmental bronchioles, subsegmental bronchioles, bronchial smooth muscle, connective tissue, and cartilaginous plates. The diaphragm can be identified in its early stage of development.

Pseudoglandular Period

The **pseudoglandular period** includes the developmental processes that occur between the 6th and the 16th weeks of gestation. During the 6th week, all the segments are present and the subsegmental bronchi are also well represented. The subsegmental bronchi continue to undergo further branching, and by the 16th week all the subsegmental bronchi are present.

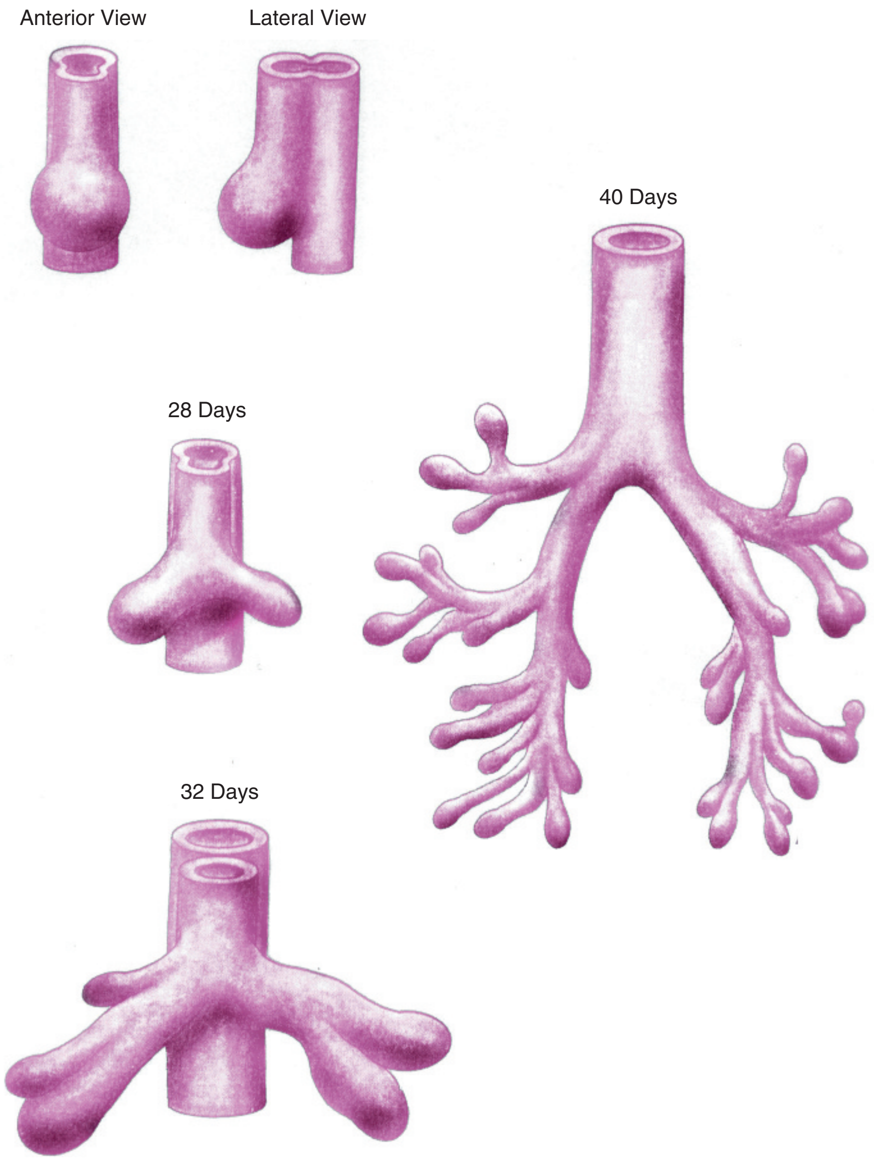
By the 10th week, ciliated columnar epithelial cells, a deeper basal layer of irregular cells, and a primitive basement membrane appear in the conducting airways. Goblet cells also begin to appear in the trachea and large bronchi. Between the 10th and 14th weeks, there is a sudden burst of bronchial branching. It is estimated that as many as 75 percent of the conducting airways develop at this time.

At 11 weeks of gestation, cartilage begins to appear in the lobar bronchi. Cartilaginous airways continue to form until about 24 weeks of gestation. By the 12th week, the bronchial mucous glands start to appear. Immature smooth-muscle cells are also noted at this time in the pulmonary arteries. As the tracheobronchial tree develops, new bronchial glands form until the 25th to 26th weeks of gestation. At birth, the concentration of bronchial glands is about 17 glands per square millimeter (mm^2). In the adult, the concentration drops to about 1 gland/mm^2 as a result of bronchial elongation and widening. By the 16th week, there are about 20 generations of bronchial airways.

Canalicular Period

The **canalicular period** includes the developmental events between the 17th and 26th weeks of gestation. During this time, the terminal bronchioles continue to proliferate, and primitive terminal bronchioles,

FIGURE 10-2 Schematic of the developmental events that occur in the human lung during the embryonic and pseudoglandular periods (see text for explanation).



respiratory bronchioles, and terminal saccules begin to appear and proliferate—forming the early foundation of the gas exchange unit, the acinus. The pulmonary capillaries begin to appear around the primitive alveoli. Early formation of lymphatic vessels appear. In addition, the alveoli begin to differentiate into Type I and Type II cells and traces of pulmonary surfactant begin to appear. A fetus born at the end of this phase (between 24 and 26 weeks' gestation) may survive with intensive neonatal care intervention.

Terminal Saccular Period

The **terminal saccular period** is between the 26th and 40th weeks of gestation. The structures that appeared in the canalicular period continue to proliferate, and the entire acinus (i.e., respiratory bronchioles, alveolar ducts, alveolar sacs, and alveoli) continues to expand and form cylindrical-shaped terminal saccules. The terminal saccules subsequently change into alveoli. The alveolar cells continue to differentiate into Type I and Type II cells. The Type II cells progressively increase the production of pulmonary surfactant during this period. By the end of the stage, the lungs should be mature enough to provide ample gas exchange.

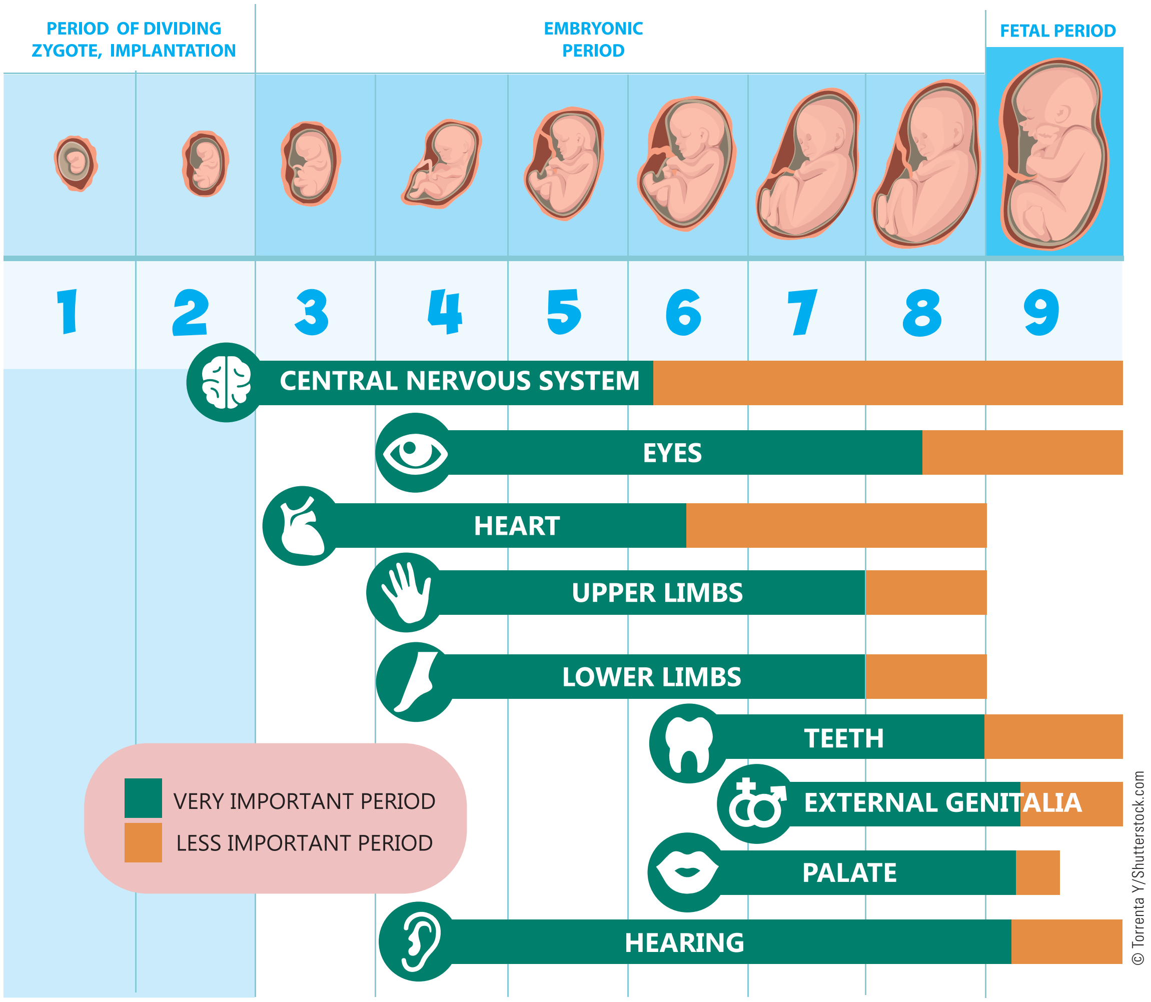
Alveolar Period

The alveolar period begins about 32 weeks' gestation and continues through childhood (8 to 10 years of age). At the end of this phase, the number of alveolar-capillary units increases to about 300 million. The extraordinary proliferation of alveoli helps to explain why young children, who have experienced various lung traumas during the neonatal and pediatric periods, frequently "outgrow" their lung problems.

Figure 10–3 provides an overview of important developmental stages of the fetus—such as the central nervous system, eyes, heart, limbs, teeth, external genitalia, palate, and hearing.

Although pulmonary capillaries begin to appear at the 24th week, the air–blood interface between the alveoli and the pulmonary capillaries is poorly defined. Between the 26th and 28th weeks' gestation, the air–blood interface and the quantity of pulmonary surfactant begin to be sufficient enough to support life. By the 34th week, the respiratory acini are well developed. The smooth-muscle fibers in the conducting airways begin to appear during the last few weeks of gestation. These muscles continue to mature after birth.

FIGURE 10-3 Important developmental stages of the fetus.



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Clinical Connection 10-1

Case Study—Adverse Effects of a Premature Birth on the Cardiopulmonary System

In the Clinical Application Case 1 (page 406), the respiratory therapist is called to help care for a 1620-g (3-lb 9-oz) baby boy who was born 12 weeks early. This case illustrates the possible adverse effects of a premature birth on the infant's alveolar-capillary gas exchange units and pulmonary circulation.

Placenta

Following conception, the fertilized egg moves down the **uterine tube** (Fallopian tube) and implants into the wall of the uterus. The placenta develops at the point of implantation. Throughout fetal life, the placenta transfers maternal oxygen and nutrients to the fetus and moves waste products out of the fetal circulation. When fully developed, the placenta appears as a reddish-brown disk about 20 cm long and 2.5 cm thick. The placenta consists of about 15 to 20 segments called **cotyledons** (Figure 10–4). Each cotyledon is composed of **fetal vessels**, **chorionic villi**, and **intervillous spaces** (Figure 10–5). The cotyledons provide an interface between the maternal and fetal circulation.

Deoxygenated blood is carried from the fetus to the placenta by way of two **umbilical arteries**, which are wrapped around the **umbilical vein** (see Figure 10–5). Normally, the P_{O_2} in the umbilical arteries is about 20 mm Hg and the P_{CO_2} is about 55 mm Hg. Once in the placenta, the umbilical arteries branch and supply each cotyledon. As the umbilical arteries enter the cotyledon, they again branch into the fetal vessels, which then loop around the internal portion of the fingerlike projections of the chorionic villi. Externally, the chorionic villi are surrounded by the intervillous space (see Figure 10–5).

Maternal blood from the uterine arteries enters the intervillous space through the **spiral arterioles**. The spiral arterioles continuously spurt jets of oxygenated blood and nutrients around the chorionic villi. Although the maternal blood P_{O_2} is usually normal during the last trimester of pregnancy (80 to 100 mm Hg), the P_{CO_2} is frequently lower than expected (about 33 mm Hg). This decrease in maternal P_{CO_2} is caused by the alveolar hyperventilation that develops as the growing infant restricts the mother's diaphragmatic excursion.

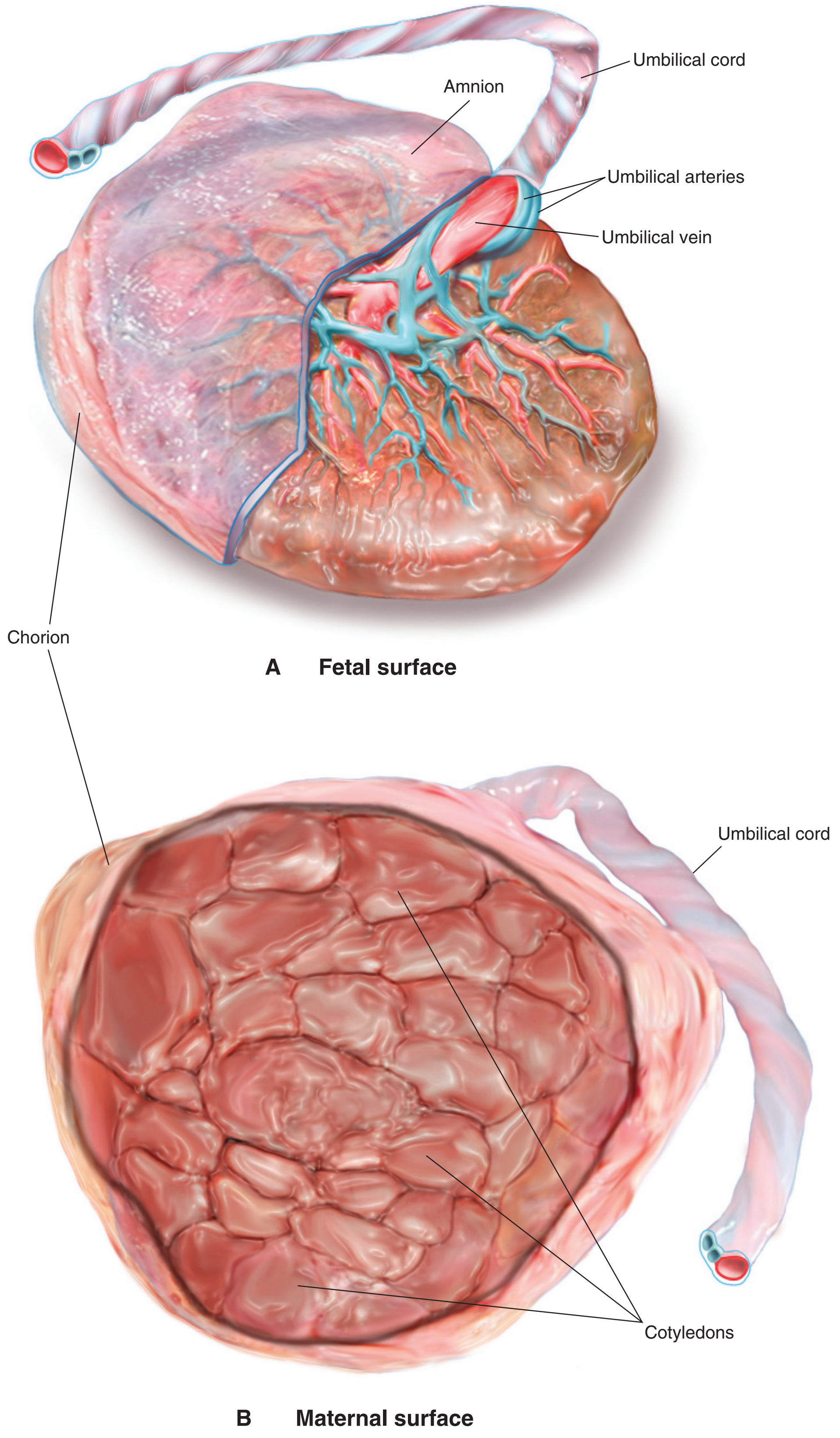
Once in the intervillous space, oxygen and nutrients in the maternal blood move through the tissues of the chorionic villi and enter the fetal blood. Oxygen transfers from the maternal to fetal blood because of the (1) maternal-fetal P_{O_2} gradient, (2) higher hemoglobin concentration in the fetal blood compared with that of maternal blood, and (3) greater affinity of fetal hemoglobin (Hb F) for oxygen than that of adult hemoglobin (Hb A). While the maternal oxygen and nutrients move into the fetal blood, carbon dioxide (P_{CO_2} of about 55 mm Hg) and other waste products move out of the fetal blood and enter the maternal blood. The blood-to-blood barrier (chorionic villi) is about 3.5 μm thick.

Oxygenated fetal blood (actually a P_{O_2} of about 30 mm Hg and a P_{CO_2} of about 40 mm Hg) flows out of the chorionic villi via the fetal vessels and returns to the fetus by way of the umbilical vein (see Figure 10–5). The wide variance between the maternal and fetal P_{O_2} and P_{CO_2} is thought to be caused by the following factors:

- The placenta itself is an actively metabolizing organ.
- The permeability of the placenta varies from region to region with respect to respiratory gases.
- There are fetal and maternal vascular shunts.

The fetal waste products in the maternal blood move out of the intervillous space by virtue of the arteriovenous pressure gradient. The pressure in the spiral arteries is about 75 mm Hg, and the pressure of the **venous orifices**, located adjacent to the spiral arteries, is about 8 mm Hg.

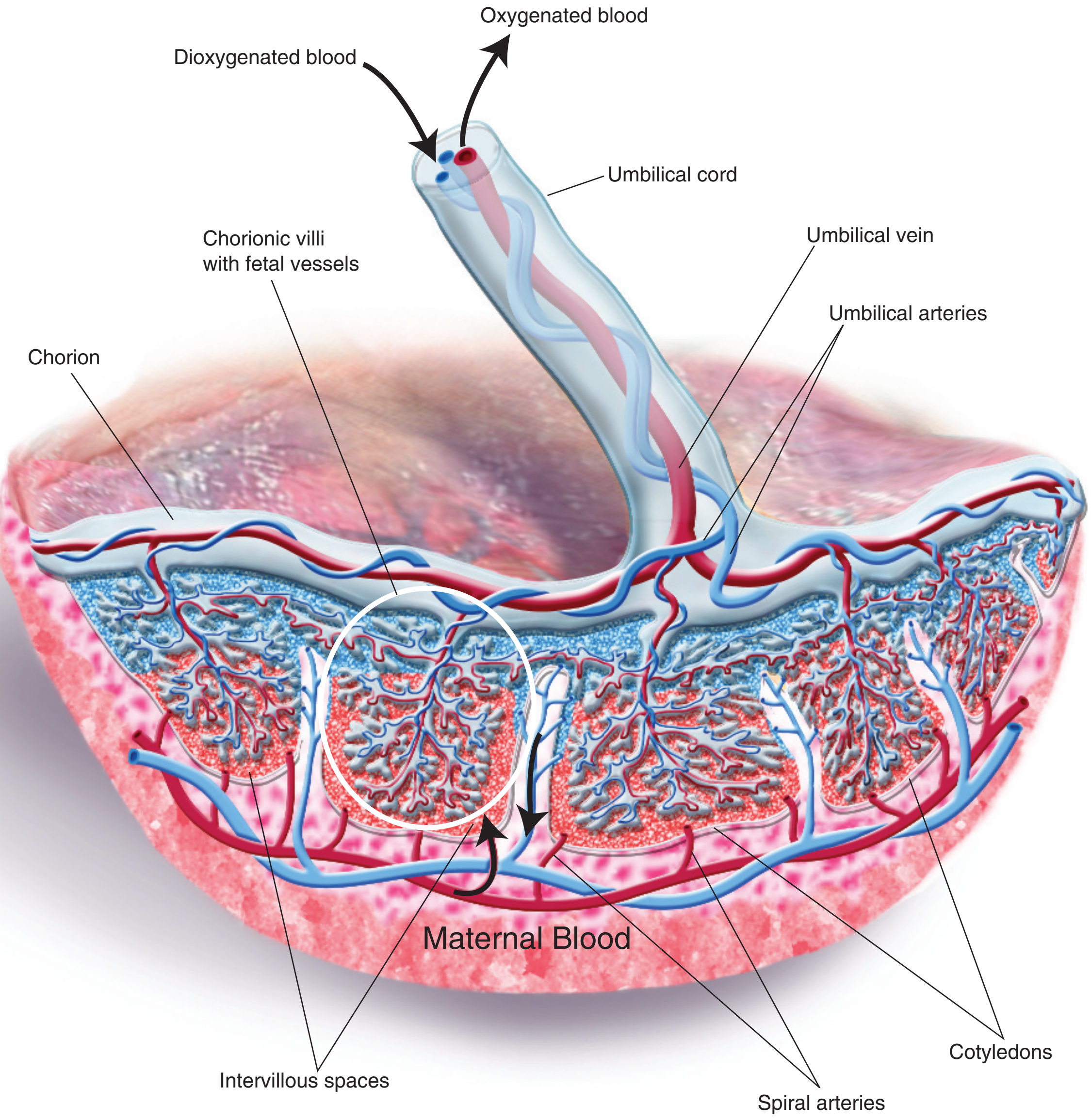
FIGURE 10-4 The placenta: **(A)** fetal surface; **(B)** maternal surface.


Umbilical cord
Amnion
Umbilical arteries
Umbilical vein
Chorion
Umbilical cord
Cotyledons

A Fetal surface

B Maternal surface

FIGURE 10-5 Anatomic structure of the placental cotyledon.


Oxygenated blood
Dioxygenated blood
Umbilical cord
Umbilical vein
Chorionic villi with fetal vessels
Umbilical arteries
Chorion
Maternal Blood
Cotyledons
Intervillous spaces
Spiral arteries

Clinical Connection 10-2

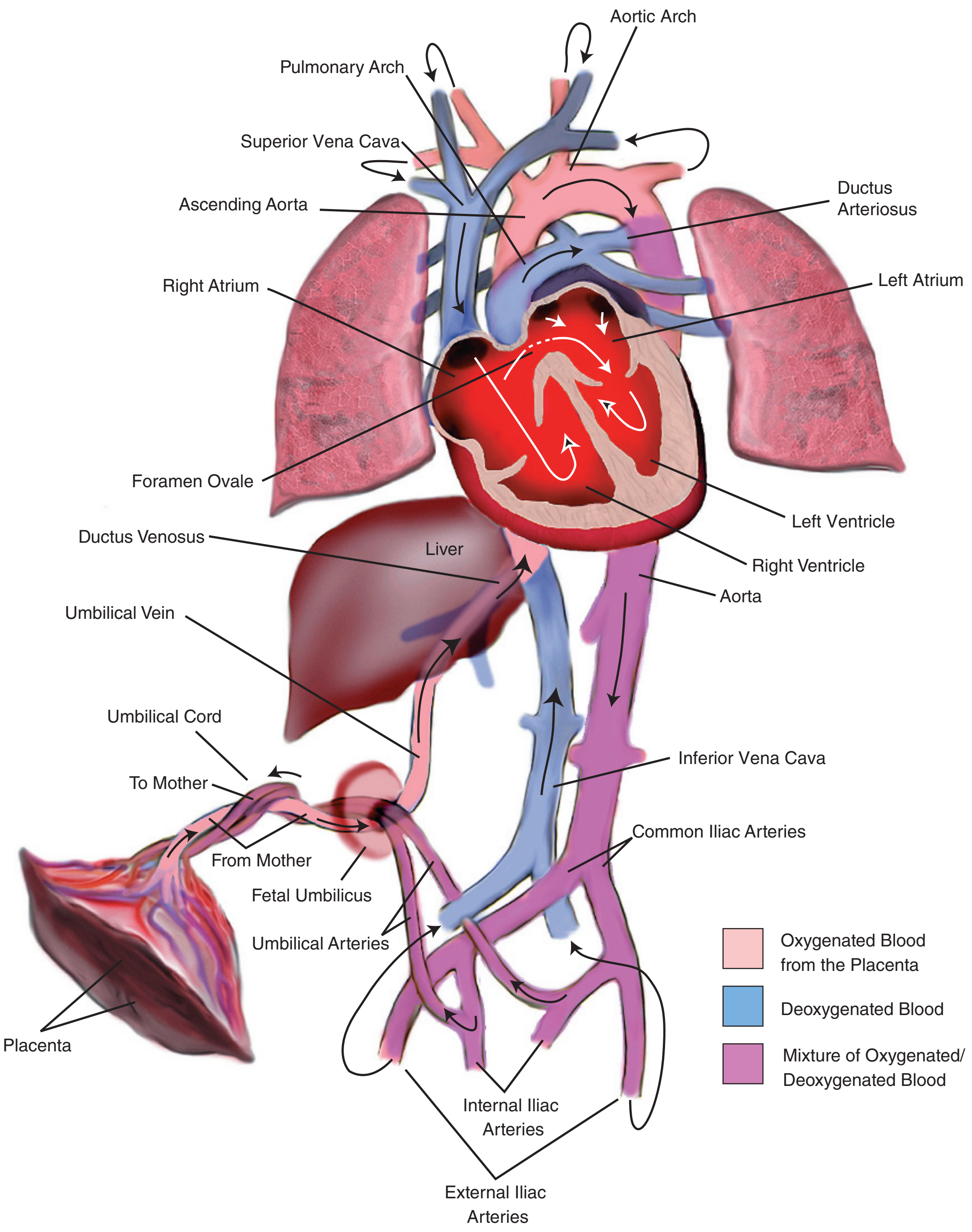
Case Study—The Placenta as an Important Lifeline between Mother and Baby

In the Clinical Application Case 2 (page 407), the respiratory therapist is called to help care for a 1610-g (3-lb 7-oz) baby girl born 6 weeks early. The baby was delivered via a cesarean section shortly after the mother was diagnosed with having *abruptio placenta*—the premature partial or total separation of the placenta from the uterus. This case illustrates the important role of the placenta as a lifeline between the mother and the baby during fetal life.

Fetal Circulation

The **umbilical vein** carries oxygenated blood (Pa_{O_2} of about 30 mm Hg) and nutrients from the placenta to the fetus (Figure 10–6). The umbilical vein enters the navel of the fetus and ascends anteriorly to the liver. About one-half of the blood enters the liver, and the rest flows through the **ductus venosus** and enters the

FIGURE 10-6 Fetal circulation.


Aortic Arch
Pulmonary Arch
Superior Vena Cava
Ascending Aorta
Ductus Arteriosus
Right Atrium
Left Atrium
Foramen Ovale
Left Ventricle
Ductus Venosus
Liver
Right Ventricle
Aorta
Umbilical Vein
Umbilical Cord
Inferior Vena Cava
To Mother
Common Iliac Arteries
From Mother
Fetal Umbilicus
Umbilical Arteries
Oxygenated Blood from the Placenta
Deoxygenated Blood
Mixture of Oxygenated/ Deoxygenated Blood
Placenta
Internal Iliac Arteries
External Iliac Arteries

inferior vena cava. This results in oxygenated fetal blood mixing with deoxygenated blood from the lower parts of the fetal body. The newly mixed fetal blood then travels up the inferior vena cava and enters the **right atrium**, where it again mingles with deoxygenated blood from the **superior vena cava**.

Once in the right atrium, most of the blood flows directly into the left atrium through the **foramen ovale**. While in the left atrium, the fetal blood again mingles with a small amount of deoxygenated blood from the pulmonary veins. The blood then enters the left ventricle and is pumped primarily to the heart and brain.

The rest of the blood in the right atrium moves into the right ventricle and is pumped into the pulmonary artery. Once in the pulmonary artery, most of the blood bypasses the lungs and flows directly into the aorta through the **ductus arteriosus**. A small amount of blood (about 15 percent) flows through the lungs and returns to the left atrium via the pulmonary veins. The Pa_{O_2} in the descending aorta is about 20 mm Hg. Downstream, the **common iliac arteries** branch into the **external** and **internal iliacs**. The blood in the internal iliac branch passes into the umbilical arteries and again flows back to the placenta to pick up oxygen and to drop off waste products.

After birth—and once the lungs and the renal, digestive, and liver functions are established—the special structures of the fetal circulation are no longer required. These special structures go through the following changes:

- The placenta is expelled by the mother.
- The umbilical arteries atrophy and become the lateral umbilical ligaments.
- The umbilical vein becomes the round ligament *(ligamentum teres)* of the liver.
- The ductus venosus becomes the *ligamentum venosum,* which is a fibrous cord in the liver.
- The flap on the foramen ovale usually closes (as a result of the increased left atrium blood pressure) and becomes a depression in the interatrial septum called the *fossa ovalis.*
- The ductus arteriosus atrophies and becomes the *ligamentum arteriosum*.

Fetal Lung Fluids

It is estimated that at birth, the lungs are partially inflated with liquid approximately equal to the newborn's functional residual capacity. It was once thought that this liquid originated from the aspiration of amniotic

Clinical Connection 10-3

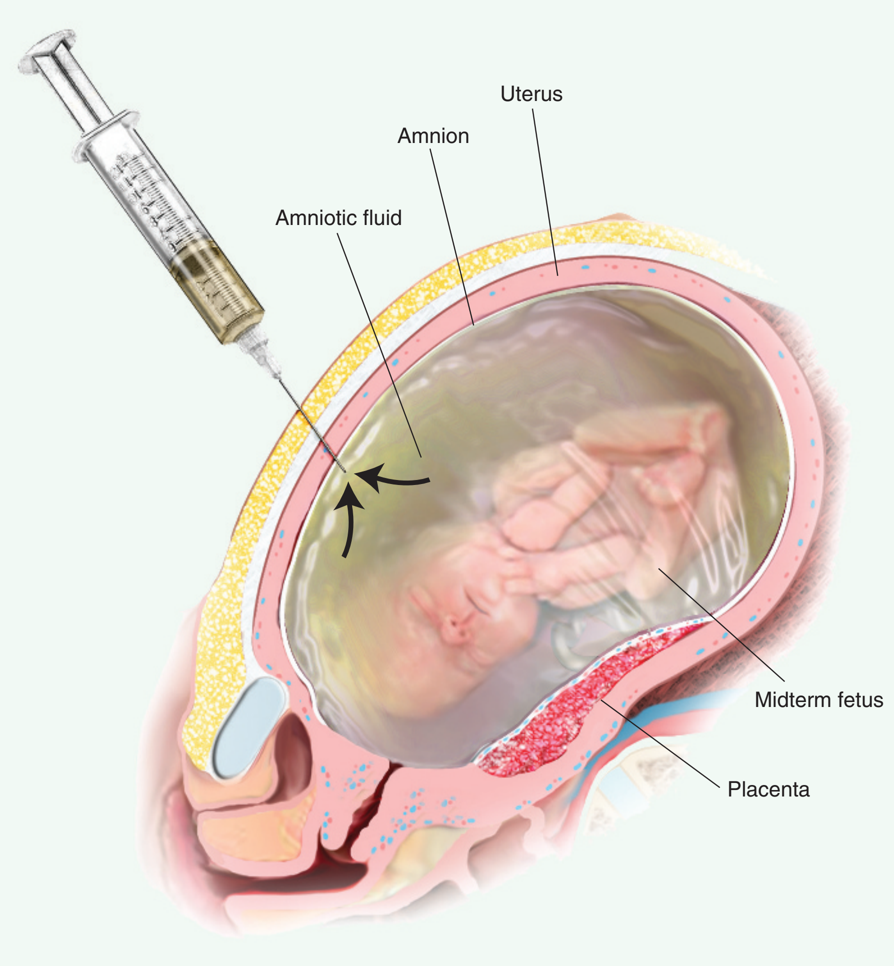
Amniocentesis

Amniocentesis is a procedure used to diagnose fetal abnormalities. As shown in Figure 10–7, an amniocentesis is performed by gently inserting a needle through the uterus and drawing out a small sample of amniotic fluid surrounding the fetus for laboratory analysis. The results from the fetal cells and other substances can reveal a number of important things about fetal development, including the lung maturity of the fetus, the bilirubin level (used to evaluate Rh incompatibility), the creatinine level (used to assess kidney function and maturity), the presence of any genetic disorders (assessed from cellular examinations), and evidence of *meconium* (first fetal stool—a thick and sticky, usually greenish to black material) in the amniotic fluid. Amniotic fluid stained with meconium indicates fetal asphyxia and possible meconium aspiration.

(*Continued*)

Clinical Connection 10-3, Continued

FIGURE 10-7 Amniocentesis.



Courtesy T. Des Jardins, WindMist LLC

fluid because the fetus normally demonstrates periods of rapid and irregular breathing during the last trimester of gestation. It is now known, however, that this is not the case. The fluid apparently originates from the alveolar cells during fetal development. At birth, the fluid is removed from the lungs during the first 24 hours of life primarily by the following mechanisms:

- About one-third of the fluid is squeezed out of the lungs as the infant passes through the birth canal.
- About one-third of the fluid is absorbed by the pulmonary capillaries.
- About one-third of the fluid is removed by the lymphatic system.

Number of Alveoli at Birth

About 24 million primitive alveoli are present at birth. This number, however, represents only about 10 percent of the adult gas exchange units. The number of alveoli continues to increase until about 12 years of age. Thus, it is important to note that respiratory problems during childhood can have a dramatic effect on the anatomy and physiology of the mature pulmonary system.

Clinical Connection 10-4

Tests Used to Determine Lung Maturity in the Fetus

There are several clinical tests available that can be used to measure the lung maturity of the fetus. These include the **lecithin to sphingomyelin ratio**, the presence of **phosphatidylglycerol**, and more recently, the **lamellar body count**.

1. The **lecithin to sphingomyelin (L:S) ratio** is a common test of the fetal amniotic fluid to measure the maturity of the fetal lung. An amniotic fluid sample is collected—by means of a procedure called an *amniocentesis*—and processed. When the concentration of lecithin is two times greater than sphingomyelin—an L:S ratio of 2:1—the fetus lung development should be mature enough to produce sufficient pulmonary surfactant at birth. The L:S ratio is relatively easy to measure, and the validity and reliability of the test is good.
2. The test for **phosphatidylglycerol (PG)** is also useful to evaluate lung maturity. PG is a phospholipid found in pulmonary surfactant. The presence of PG in the amniotic fluid indicates a low risk of RDS.
3. The **lamellar body count (LBC)** in the amniotic fluid highly correlates with the L:S ratio and the PG levels. Fetal lung maturity is present when the LBC is $>$50,000 mcL. The advantage of the lamellar body count is that it can be easily and quickly obtained, requires a small amount of amniotic fluid, and is relatively inexpensive.

Birth

Moments after birth, an intriguing and dramatic sequence of anatomic and physiologic events occur. The function of the placenta is suddenly terminated, the lungs rapidly establish themselves as the organs of gas exchange, and all the features of adult circulation are set in place.

First Breath

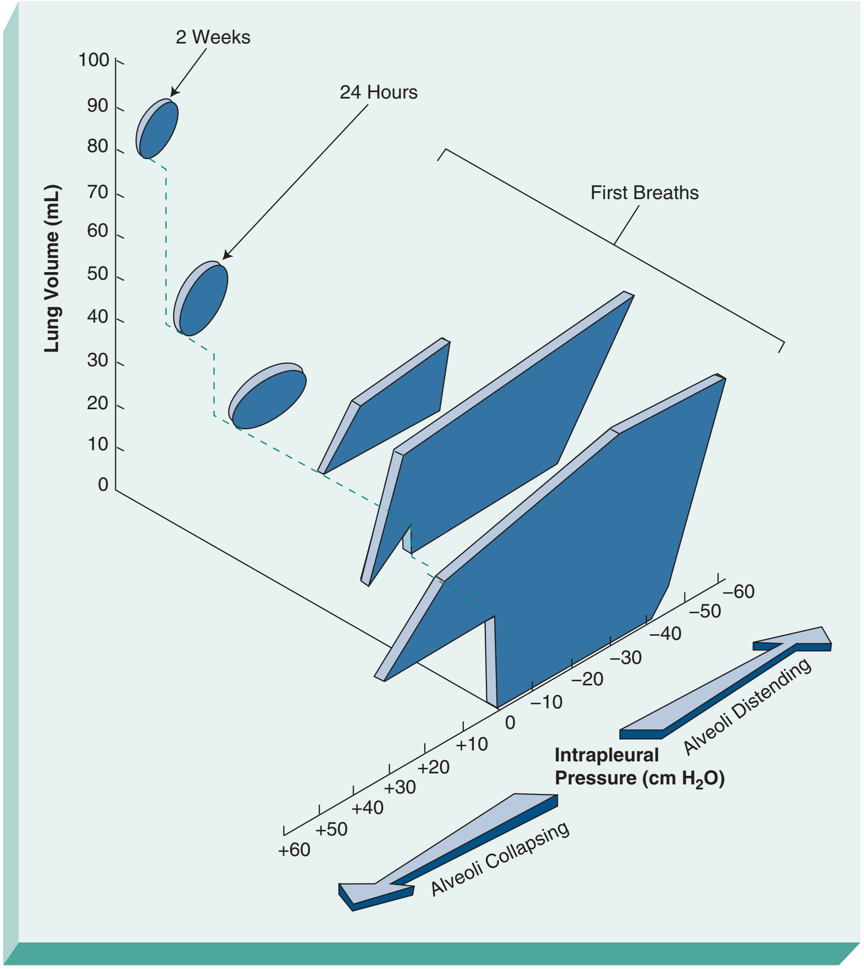
At birth, the infant is bombarded by a variety of external sensory stimuli (e.g., thermal, tactile, visual). At the same time, the placenta ceases to function, causing the fetal blood P_{O_2} to decrease, the P_{CO_2} to increase, and the pH to decrease. Although the exact mechanism is unknown, the sensitivity of both the central and the peripheral chemoreceptors of the newborn increases dramatically at birth. In response to all these stimuli, the infant *inhales.*

To initiate the first breath, however, the infant must generate a remarkable negative intrapleural pressure to overcome the viscous fluid in the lungs. It is estimated that the intrapleural pressure must decrease to about −40 cm H_2O before any air enters the lungs. Intrapleural pressures as low as −100 cm H_2O have been reported. About 40 mL of air enter the lungs during the first breath. On exhalation, the infant expels about one-half of the volume obtained on the first breath, thus establishing the first portion of the residual volume. Figure 10–8 illustrates the typical pressure-volume changes of the lungs that occur in the newborn during the first 2 weeks of life. The average *lung compliance* of the newborn is about 0.005 L/cm H_2O (5 mL/cm H_2O); the *airway resistance* is about 30 cm H_2O/L/sec.

Circulatory Changes at Birth

There are six fetal circulation structures that are no longer needed after birth—the **umbilical arteries**, **placenta**, **umbilical vein**, **ductus venosus**, **foramen ovale**, and **ductus arteriosus**. When the umbilical cord is clamped and cut, the two *umbilical arteries,* the *placenta,* and the *umbilical vein* no longer function. The placenta is shed from the mother's uterus. The umbilical vein remaining in the infant's body eventually becomes the **round ligament** of the liver, and the ductus venosus becomes the **ligamentum venosum**.

FIGURE 10-8 The pressure-volume changes of the newborn's lungs during the first 2 weeks of life.



In regard to the foramen ovale and ductus arteriosus, the following chain of events must occur—in this precise sequence—in order to stop their fetal circulation functions and, thereby, allow normal circulation to ensue:

1. As the infant inhales for the first time, the pulmonary vascular resistance falls dramatically. The major mechanisms that account for the decreased pulmonary vascular resistance are (a) the sudden increase in the alveolar P_{O_2}, which offsets the hypoxic vasoconstriction; (b) the removal of fluid from the lungs, reducing the external pressure on the pulmonary vessels; and (c) the mechanical increase in lung volume, which widens the caliber of the extra-alveolar vessels.
2. As the pulmonary vascular resistance decreases, a greater amount of blood flows through the lungs and, therefore, more blood returns to the left atrium. This causes the pressure in the left atrium to increase and the flap of the *foramen ovale* to close. The closure of the foramen ovale is further aided by the fall in pressure that occurs in the right atrium as the umbilical flow ceases. Complete structural closure, however, usually takes about 9 months or more. Eventually, the foramen ovale becomes a small depression, called the **fossa ovalis**, in the wall of the right atrial septum.
3. A few minutes later, the smooth muscles of the *ductus arteriosus* constrict in response to the increased P_{O_2}. The newborn's P_{O_2} must increase to more than 45 to 50 mm Hg in order for the ductus arteriosus to close. Under normal conditions, the ductus arteriosus eventually forms a fibrous cord called the **ligamentum arteriosum**.

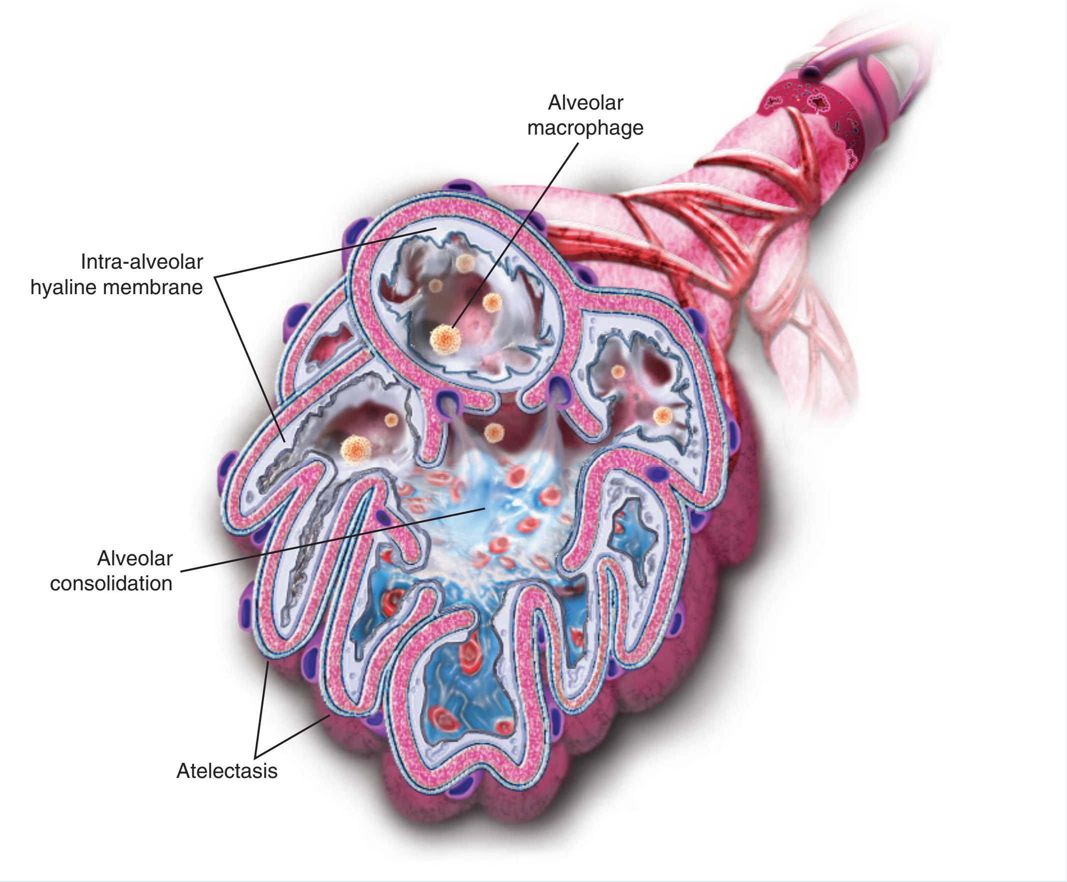
Clinical Connection 10-5

Respiratory Distress Syndrome

Respiratory distress syndrome (RDS) is the most common cause of respiratory failure in the preterm baby (Figure 10–9). The *normal-term* baby is between 38 and 42 weeks' gestation; a baby born before 38 weeks' gestation is called a *preterm baby* (premature). About 50 percent of the babies born between 26 and 28 weeks' gestation develop respiratory distress syndrome (RDS). About 25 percent of the babies born between 30 and 31 weeks' gestation develop RDS. These babies are born before their Type II alveolar cells are mature enough to make an adequate amount of pulmonary surfactant. As a result, the baby's alveolar surface tension increases and causes the alveoli to collapse (atelectasis).

During the early stages of RDS, the treatment of choice is **continuous positive airway pressure (CPAP)**. The therapeutic benefits of CPAP include (1) the re-inflation of collapsed alveoli, (2) the decreased work of breathing, and (3) the return of the baby's oxygenation level to normal. The use of mechanical ventilation is avoided as long as possible. The administration of exogenous pulmonary surfactants may also be helpful to baby with RDS. Common exogenous preparations are **beractant** (Survanta®), **calfactant** (Infasurf®), and **poractant alfa** (Curosurf®).

FIGURE 10-9 Cross-sectional view of alveoli with respiratory distress syndrome. Pathology includes (1) interstitial and alveolar edema and hemorrhage, (2) alveolar consolidation, (3) intra-alveolar hyaline membrane, (4) pulmonary surfactant deficiency, (5) atelectasis, (6) and pulmonary arterial hypoxia-induced vasoconstriction and vasospasm.



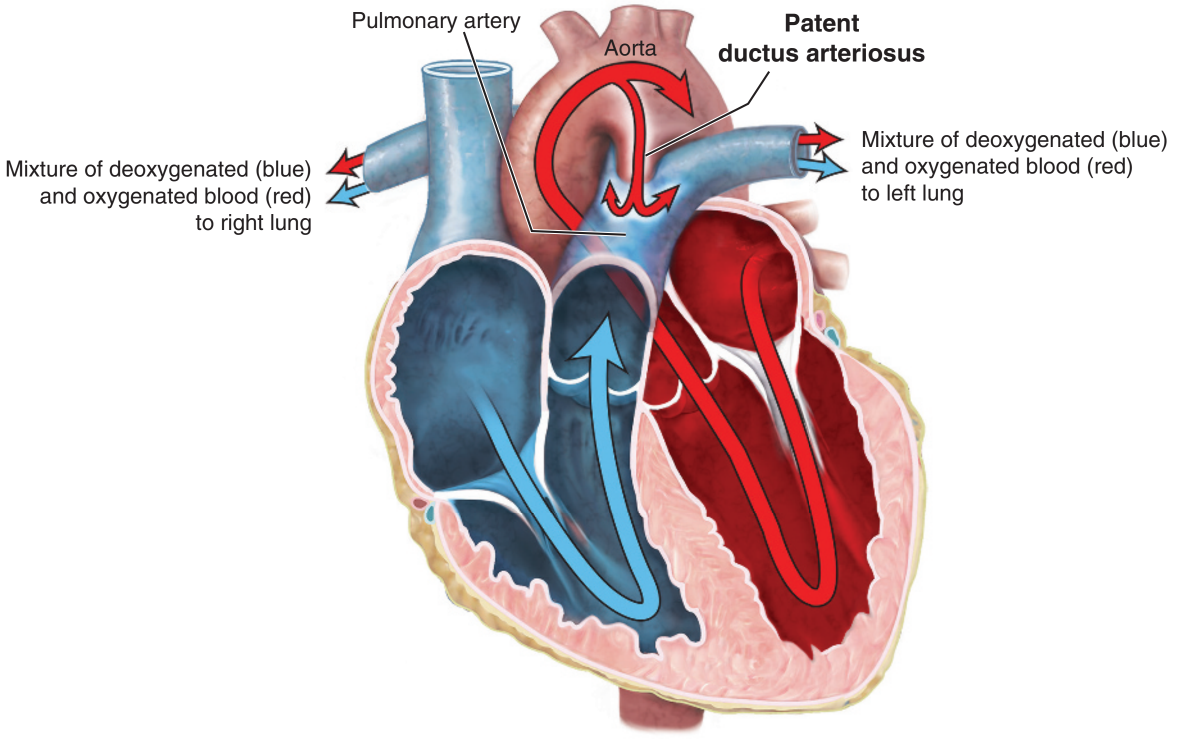
4. If this P_{O_2} level is not reached, the ductus arteriosus will remain open, and the pulmonary vascular resistance will remain elevated, producing the syndrome known as **persistent pulmonary hypertension of the neonate (PPHN)** (previously known as persistent fetal circulation). Furthermore, should the neonate's P_{O_2} increase sufficiently to close the ductus arteriosus but then fall within the first 24 to 48 hours after birth, the ductus arteriosus will reopen. It is believed that other substances released at birth (such as bradykinin, serotonin, and prostaglandin inhibitors) contribute to the constriction of the ductus arteriosus.

Clinical Connection 10-6

Patent Ductus Arteriosus

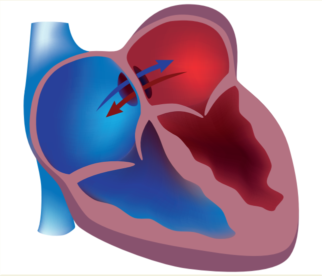
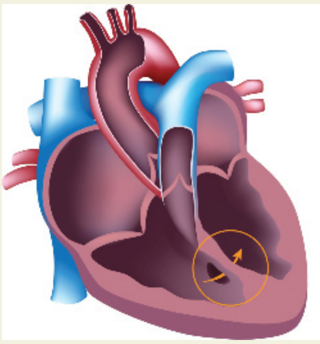
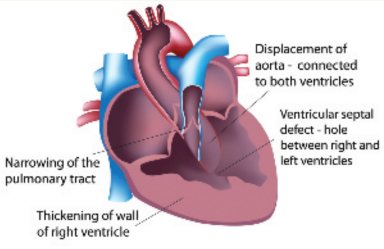
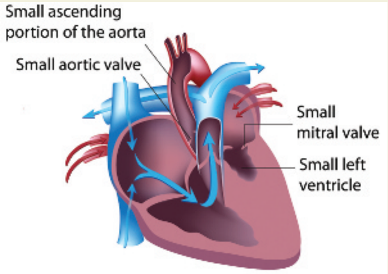
Patent ductus arteriosus is a congenital heart defect of the ductus arteriosus, which is normally open during fetal life but fails to close shortly after birth. As a result, a portion of the oxygenated blood from the aorta (which has a higher blood pressure) flows through the open ductus back to the pulmonary artery (Figure 10–10). The pathophysiologic effect of a PDA is a *left-to-right* shunt—which, in turn, leads to an excessive blood flow through the pulmonary circulation. Excessive pulmonary engorgement leads to pulmonary edema, pulmonary hemorrhage, and a decreased lung compliance that may require mechanical ventilation and positive-end-expiratory-pressure (PEEP). Other common congenital heart defects associated with the newborn are shown in Table 10–1.

FIGURE 10-10 Cross-sectional view of a heart with a patent ductus arteriosus. Pathology includes (1) failure of the ductus arteriosus to close after birth, (2) left-to-right shunt, (3) excessive pulmonary blood flow, (4) pulmonary engorgement, (5) pulmonary edema, (6) pulmonary hemorrhage, and (7) a decreased lung compliance.


Pulmonary artery
Aorta
Patent ductus arteriosus
Mixture of deoxygenated (blue) and oxygenated blood (red) to right lung
Mixture of deoxygenated (blue) and oxygenated blood (red) to left lung

Clinical Connection 10-6, Continued

TABLE 10-1 Common Congenital Heart Defects

Congenital Heart Defect	Description
Atrial septal defect 	**Atrial septal defect (ASD)** is a congenital heart defect in which there is a hole in the septal wall between the right and left atrium. The degree of pathophysiology associated with an ASD depends on (1) the pulmonary and systemic vascular resistances, (2) the compliance of the left and right ventricles, and (3) the size of the ASD.
Ventricular septal defect 	A **ventricular septal defect (VSD)** is a congenital heart defect in which there is an opening in the ventricular septum of the heart. There may be one or more openings in different locations of the ventricular septum. A VSD has the following two net effects: First, the influx of blood into the right ventricle from the left ventricle increases the right ventricular pressure and volume; in turn, this can lead to pulmonary hypertension, arrhythmias, and heart failure. Second, the circuitous route of blood through the lungs and back to the heart causes a volume overload and elevated pressure in the left ventricle as well.
Tetralogy of Fallot  Displacement of aorta - connected to both ventricles Ventricular septal defect - hole between right and left ventricles Narrowing of the pulmonary tract Thickening of wall of right ventricle	**Tetralogy of Fallot (TOF)** is a congenital heart defect with the following four major anatomic alterations: • Stenosis of the pulmonary artery. • Deviation of the aorta to the right. • Ventricular septal defect. • Right ventricular hypertrophy. The pathophysiologic effects—and clinical symptoms—of TOF are largely dependent upon the degree of right ventricular outflow tract obstruction.
Hypoplastic left heart syndrome  Small ascending portion of the aorta Small aortic valve Small mitral valve Small left ventricle	**Hypoplastic left heart syndrome (HLHS)** is a single ventricle defect that results from the left heart not forming correctly during pregnancy. The defects include: • An underdeveloped, small left ventricle. • A nonformed or very small mitral valve. • A nonformed or very small aortic valve. • An underdeveloped or very small ascending aorta/aortic arch. • Atrial septal defect, which is life-threatening. With these defects, the left side of the heart is not capable of pumping adequate oxygenated blood through the left ventricle and out of the aorta. The degree of narrowing of the valves and the structures can be critical.

Control of Ventilation in the Newborn

Within moments after birth, the newborn infant initiates the first breath. Although they are inhibited during fetal life, the peripheral and central chemoreceptors play a major role in activating the first breath. It is not precisely understood why these chemoreceptors are dormant during fetal life but suddenly activated at birth.

Peripheral Chemoreceptors

The exact role of the peripheral chemoreceptors in the newborn is not clearly defined. It is known, however, that in both preterm and term infants, hypoxia elicits a transient rise in ventilation, followed by a marked fall. The magnitude of the increase is similar whether the infant is in the rapid eye-movement (REM) state, quiet sleep state, or awake state. The late fall, however, is less marked or is absent when the infant is in the quiet sleep state. One to 2 weeks after birth, the infant demonstrates the adult response of sustained hyperventilation. The response to hypoxia is greater and more sustained in the term infant than in the preterm infant. Although it is known that the peripheral chemoreceptors of the adult are responsive to CO_2, little information is available about the peripheral chemoreceptors' sensitivity to changes in CO_2 and pH during the neonatal period.

Central Chemoreceptors

The central chemoreceptors of the newborn respond to the elevated CO_2 levels in a manner similar to that of the adult. The response to an increased CO_2 level is primarily an increased tidal volume, with little change in inspiratory time or ventilatory rate. The response of the central chemoreceptors may be more marked with increasing gestational age.

Infant Reflexes

Trigeminal Reflex

Stimulation of the newborn's trigeminal nerve (i.e., the face and nasal and nasopharyngeal mucosa) causes a decrease in the infant's respiration and heart rate. It has been reported that even gentle stimulation of the malar region in both preterm and term infants may cause significant respiratory slowing. Thus, various procedures (such as nasopharyngeal suctioning) may be hazardous to the newborn. Clinically, facial cooling has been used as a means of terminating paroxysms of supraventricular tachycardia in the newborn.

Irritant Reflex

Epithelial irritant receptors, located throughout the airways, respond to direct tactile stimulation, lung deflation, and irritant gases. This response is mediated by myelinated vagal fibers. Based on gestational age, these receptors elicit different responses. In preterm infants of less than 35 weeks' gestation, tracheal stimulation (e.g., endotracheal suctioning or intubation) is commonly followed by respiratory slowing or apnea. In the term infant, however, stimulation causes marked hyperventilation. The inhibitory response seen in the preterm infant may be due to vagal nerve immaturity (i.e., the vagal nerves are not adequately myelinated). Unmyelinated neurons are unable to transmit high-frequency discharges.

Head's Paradoxical Reflex

Head's paradoxical reflex is a deep inspiration that is elicited by lung inflation. In other words, the infant inhales and then tops the inspiration with a deep breath before exhalation occurs. This reflex is seen in the term infant and is thought to be mediated by the irritant receptors. The head paradoxical reflex may play a role in sighing, which is frequently seen in the newborn. This reflex is thought to be valuable in maintaining lung compliance by offsetting alveolar collapse.

Clinical Parameters in the Normal Newborn

Table 10–2 lists the average pulmonary function findings of the newborn. The vital signs of the normal newborn are listed in Table 10–3. Figure 10–11 illustrates graphically the average pH, Pa_{CO_2}, HCO_3^-, and Pa_{O_2} values of the normal infant over a period of 72 hours after birth.

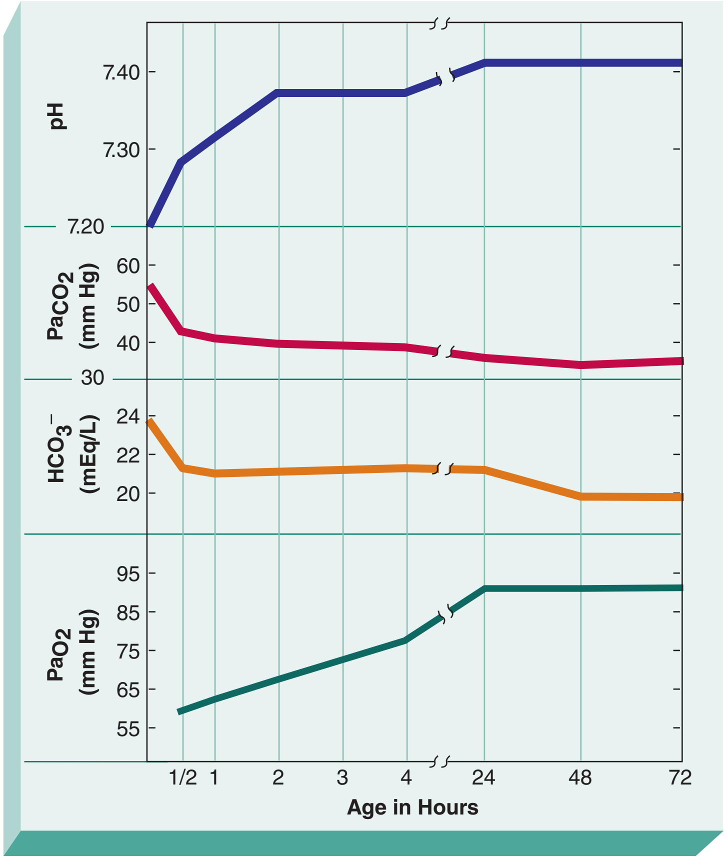
TABLE 10-2 **Approximate Lung Volumes (mL) and Capacities of the Normal Newborn**

Tidal volume (V_T)	15	Vital capacity (VC)	115
Residual volume (RV)	40	Functional residual capacity (FRC)	80
Expiratory reserve volume (ERV)	40	Inspiratory capacity (IC)	75
Inspiratory reserve volume (IRV)	60	Total lung capacity (TLC)	155

TABLE 10-3 **Vital Sign Ranges of the Normal Newborn**

Respiratory rate (RR)	35–50/min
Heart rate (HR)	130–150/min
Blood pressure (BP)	60/40–70/45 mm Hg

FIGURE 10-11 The average pH, Pa_{CO_2}, HCO_3^-, and Pa_{O_2} values of the normal infant during the first 72 hours of life.

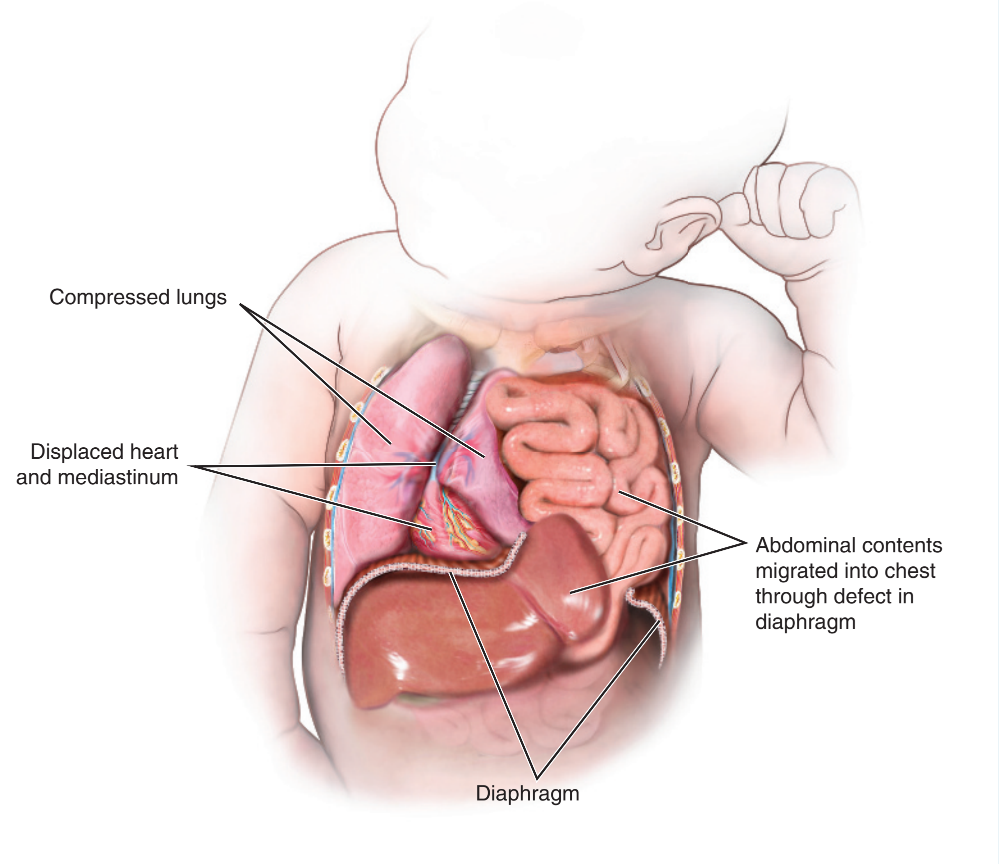


Clinical Connection 10-7

Congenital Diaphragmatic Hernia

Congenital diaphragmatic hernia (CDH) occurs when the diaphragm fails to close during prenatal development and the contents from the abdomen migrate into the chest through this hole (Figure 10–12). About 1,600 babies are born with CDH every year in the United States. This defect usually develops around 9–10 weeks' gestation. The effects of a diaphragmatic hernia are similar to the effects of a **pneumothorax**—that is, the lungs are compressed, and the heart and mediastinum are pushed to the unaffected side of the thorax (see Figure 2–28). As the condition becomes more severe, **atelectasis** and complete lung collapse may occur. Lung compliance is low. In addition, long-term lung compression in utero can cause **pulmonary hypoplasia (**or underdeveloped lungs). This can lead to decreased blood flow through the lungs and pulmonary hypertension. Treatment includes stabilizing the cardiopulmonary status and surgical repair.

FIGURE 10-12 Congenital diaphragmatic hernia. Pathology includes (1) failure of diaphragm to close during fetal development, (2) migration of abdomen contents into the chest, (3) lung compression of the affected side—usually the left side, (4) heart and mediastinum pushed to the unaffected side of the thorax—usually shifted to the right side, (5) atelectasis and lung collapse, (6) low lung compliance, (7) pulmonary hypoplasia (i.e., underdeveloped lungs), and (8) pulmonary hypertension.


Compressed lungs
Displaced heart and mediastinum
Abdominal contents migrated into chest through defect in diaphragm
Diaphragm

Clinical Connection 10-8

Neonatal/Pediatric Respiratory Care Specialty

The respiratory therapist can further broaden his or her career by pursuing additional education and training to become a credentialed **neonatal/pediatric respiratory care specialist**. The neonatal/pediatric specialist (NPS) works in children's hospitals, general hospitals, and neonatal intensive care units. The NPS is involved in treating and monitoring a variety of newborn breathing disorders. The NPS might monitor the breathing of premature babies, treat infants born with pulmonary disorders, or respond to the unique respiratory care needs of an infant in an emergency. Common respiratory disorders associated with the newborn infant include meconium aspiration syndrome, transient tachypnea of the newborn, respiratory distress syndrome, pulmonary air leak syndromes, respiratory syncytial virus infection, chronic lung disease of infancy (also known as bronchopulmonary dysplasia), and congenital diaphragmatic hernia.

The **National Board for Respiratory Care Inc. (NBRC)** administers the credentialing examination for the neonatal/pediatric respiratory care specialty. The Neonatal/Respiratory Care Specialty Examination is designed to objectively measure essential knowledge, skills, and abilities required of respiratory therapists in the specialty area. Achievement of the **Certified Respiratory Therapist (CRT)** credential, plus one year of clinical experience in neonatal/pediatric respiratory care, or the **Registered Respiratory Therapist (RRT)** credential is required for admission to the Neonatal/Pediatric Specialty Examination (www.nbrc.org).

Chapter Summary

The major cardiopulmonary physiology of the fetus and the newborn develops during four periods: embryonic, pseudoglandular, canalicular, and terminal sac. The primary components of the placenta include the cotyledons, fetal vessels, chorionic villi, intervillous spaces, umbilical arteries, umbilical vein, and spiral arterioles. The major components of fetal circulation include the umbilical vein, ductus venosus, inferior vena cava, right atrium, superior vena cava, foramen ovale, ductus ateriosus, common iliac arteries, and external and internal iliacs.

The respiratory therapist needs a knowledge base of the anatomic and physiologic sequences occurring at birth, including the first breath, circulatory changes, and persistent pulmonary hypertension of the neonate (PPHN); control of ventilation in the newborn, including the peripheral chemoreceptors, central chemoreceptors, and infant reflexes; and the clinical parameters in the normal newborn, including approximate lung volumes and capacities and vital sign ranges.

Clinical connections associated with the preceding topics include (1) a case study that illustrates the adverse effects of a premature birth on the cardiopulmonary system, (2) a case study that illustrates the importance of the placenta as a lifeline between the mother and the baby during fetal life, (3) amniocentesis, (4) tests used to determine lung maturity in the fetus, (5) respiratory distress syndrome, (6) patient ductus arteriosus, (7) congenital hernia, and (8) the neonatal/pediatric respiratory care specialty.

1 Clinical Application Case

A 1620-g (3-lb 9-oz) boy was born 12 weeks early (at 28 weeks' gestation). His Apgar scores at delivery were 4 and 5.[1] The baby's skin was cyanotic, and he was in obvious respiratory distress. He demonstrated nasal flaring and intercostal retractions. A gruntlike sound could be heard without the aid of a stethoscope during each exhalation. The baby was transferred to the neonatal intensive care unit and placed on continuous positive airway pressure (CPAP) via nasal prongs at a pressure setting of 3 cm H_2O and an inspired oxygen concentration ($F_{I_{O_2}}$) of 0.4.

The baby's vital signs were respiratory rate—64 breaths/min, blood pressure—48/22 mm Hg, and apical heart rate—175 beats/min. On auscultation, bilateral crackles could be heard. A portable chest X-ray showed a "ground-glass" appearance and air bronchogram throughout both lung fields, consistent with respiratory distress syndrome (RDS). Umbilical arterial blood gas values were pH—7.53, Pa_{O_2}—28 mm Hg, HCO_3^-—21 mEq/L, and P_{O_2}—41 mm Hg. The neonatologist entered the following diagnosis in the infant's progress notes: "IRDS and PPHN" (persistent pulmonary hypertension of the neonate).

During the next 72 hours, the infant's clinical progress was stormy. Three hours after the baby was born, he was intubated and placed on a time-cycled, pressure-limited synchronized intermittent mandatory ventilation (SIMV) rate of 35 breaths/min, inspiratory time 0.5 second, peak inspiratory pressure (PIP) of 22 cm H_2O, an $F_{I_{O_2}}$ of 0.8, and positive end-expiratory pressure (PEEP) of 7 cm H_2O. The baby received Survanta® treatments (a synthetic pulmonary surfactant) through his endotracheal tube on day 2. On day 4, his clinical condition stabilized.

Although the baby was still intubated on day 5, he no longer required SIMV. The ventilator was set on the CPAP mode at a pressure setting of 3 cm H_2O with an $F_{I_{O_2}}$ of 0.4. The baby's vital signs were blood pressure—73/48 mm Hg, heart rate (apical)—122 beats/min, and respiratory rate—40 breaths/min. Normal vesicular breath sounds were heard over both lung fields. Chest X-ray showed substantial improvement throughout both lungs. The baby's umbilical arterial blood gas values were pH—7.41, Pa_{CO_2}—38 mm Hg, HCO_3^-—24 mEq/L, and Pa_{O_2}—158 mm Hg. The $F_{I_{O_2}}$ was decreased to 0.3. The neonatologist wrote the following assessment in the patient's chart: "IRDS has significantly improved and PPHN no longer appears to be present." The baby progressively improved and was discharged 3 days later.

Discussion

This case illustrates the possible adverse effects of a premature birth on the infant's alveolar-capillary gas exchange units and pulmonary circulation. During fetal development, the alveolar-capillary system and the quantity of pulmonary surfactant usually are not sufficient to support life until the 28th week of gestation or beyond. In this case, the baby was born at the very beginning of this time period. Thus, because of the immaturity of the baby's alveolar-capillary system, the ability of the type II cells to produce pulmonary surfactant was inadequate.

As a result of the insufficient amount of pulmonary surfactant, the pathologic processes of a common newborn respiratory disorder called respiratory distress syndrome (RDS) developed. The anatomic alterations of the lungs associated with RDS include interstitial and intra-alveolar edema and hemorrhage, alveolar consolidation, intra-alveolar hyaline membrane formation, and atelectasis. All of these pathologic processes cause the alveolar-capillary membrane's thickness to increase. As this condition progressively worsened, the diffusion of oxygen between the alveoli and the pulmonary capillary blood decreased, and the infant's lung compliance decreased. Clinically, the decreased diffusion of oxygen was manifested by cyanosis, increased respiration rate and heart rate, and decreased Pa_{O_2}. The decreased lung compliance was manifested by nasal flaring, intercostal retractions, exhalation grunting, bilateral crackles, and a ground-glass appearance and air bronchogram on the chest X-ray.

Finally, because the baby's Pa_{O_2} was less than 45 mm Hg shortly after birth, the ductus arteriosus remained patent, producing the syndrome known as *persistent pulmonary hypertension of the neonate* (PPHN). As the infant's condition improved and his Pa_{O_2} increased, the ductus arteriosus closed and the signs and symptoms associated with PPHN disappeared. At the time of this writing, the baby was a perfectly normal 3-year-old boy who was attending half-day preschool sessions 5 days per week.

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[1] The Apgar score evaluates five factors: heart rate, respiratory effort, muscle tone, reflex irritability, and color. Each factor is rated 0, 1, or 2. The scoring system provides a clinical picture of the infant's condition following delivery. An Apgar score is taken at 1 minute after delivery. A second Apgar score is taken at 5 minutes after delivery to assess the infant's ability to recover from the stress of birth and adapt to extrauterine life. The baby is usually considered to be out of danger when the score is greater than 7.

2 Clinical Application Case

While in her third trimester of pregnancy, a 28-year-old woman experienced vaginal bleeding, abdominal pain, uterine tenderness, and uterine contractions. Concerned, she alerted her husband, who immediately drove her to the hospital. In the emergency department, a provisional diagnosis of *abruptio placentae* (premature partial or total separation of the placenta from the uterus) was made. Because of the excessive hemorrhage, the medical staff felt that the abruptio placentae was extensive and that both the mother and the fetus were in a life-threatening situation. The patient received medication—STAT—for shock and blood replacement. She was then transferred to surgery and prepped for a cesarean section. Shortly after the delivery of the baby (and placenta), the bleeding stopped. The presence of a near-total abruptio placentae was confirmed during the surgery.

The initial assessment of the baby showed a premature female infant born 6 weeks early (at 34 weeks' gestation). She weighed only 1610 g (3 lb 7 oz). Her first Apgar score at delivery was 4. Her heart rate was less than 100 beats/min, respiratory rate was weak and irregular, skin color was blue, she demonstrated no grimace reflex when suctioned, and her muscle tone showed only moderate flexion. The baby was manually ventilated aggressively with an inspired oxygen concentration ($F_{I_{O_2}}$) of 1.0 and responded favorably within a few minutes. The second Apgar score was 8. Her heart rate was greater than 100 beats/min, she had a strong cry, her skin was pink, she demonstrated a grimace reflex when suctioned, and her muscle tone was improved.

The baby was transferred to the neonatal intensive care unit for close observation. Two hours later, the baby's vital signs were respiratory rate—44 breaths/min, blood pressure—66/42 mm Hg, and apical heart rate—135 beats/min. On auscultation, normal vesicular breath sounds were heard bilaterally. A portable chest X-ray was normal. The baby's umbilical arterial blood gas values were pH—7.33, Pa_{CO_2}—44 mm Hg, HCO_3^-—23 mEq/L, and Pa_{O_2}—52 mm Hg. Four days later, both the mother and the baby were discharged in good health.

Discussion

This case illustrates the important function of the placenta as a lifeline between the mother and the baby during fetal life. Because the placenta separated from the wall of the uterus, the maternal–placentae–fetal interface was seriously compromised. In short, the ability of the fetus to absorb oxygen, nutrients, and other substances and excrete carbon dioxide and other wastes was interrupted. Complete separation brings about immediate death of the fetus. Bleeding from the site of separation may cause abdominal pain, uterine tenderness, and uterine contraction. Bleeding may be concealed within the uterus or may be evident externally, sometimes as sudden massive hemorrhage (as in this case). In severe cases, shock and death can occur in minutes. A cesarean section must be performed immediately. Fortunately, in this case, the mother and the baby were treated in a timely manner.

Review Questions

1. During the embryonic period, the lungs first appear at about the
   A. 10th day after fertilization
   B. 24th day after fertilization
   C. 6th week after fertilization
   D. 12th week after fertilization

2. The lungs are usually sufficiently mature to support life by the
   A. 24th week of gestation
   B. 28th week of gestation
   C. 32nd week of gestation
   D. 36th week of gestation

3. At birth, the number of alveoli represents about how much of the total adult gas exchange units?
   A. 10 percent
   B. 20 percent
   C. 30 percent
   D. 40 percent

4. The number of alveoli continues to increase until about

A. 6 years of age
B. 8 years of age
C. 10 years of age
D. 12 years of age

5. The average P_{O_2} in the umbilical arteries during fetal life is about

A. 20 mm Hg
B. 40 mm Hg
C. 60 mm Hg
D. 80 mm Hg

6. The average P_{O_2} in the umbilical vein during fetal life is about

A. 20 mm Hg
B. 30 mm Hg
C. 40 mm Hg
D. 50 mm Hg

7. The average P_{CO_2} in the umbilical arteries during fetal life is about

A. 25 mm Hg
B. 35 mm Hg
C. 45 mm Hg
D. 55 mm Hg

8. In the placenta, maternal blood is continuously pumped through the

A. Umbilical arteries
B. Chorionic villi
C. Fetal vessels
D. Intervillous space

9. In the fetal circulation, once blood enters the right atrium, most of the blood enters the left atrium by passing through the

A. Ductus arteriosus
B. Ductus venosus
C. Pulmonary arteries
D. Foramen ovale

10. Shortly after birth, the ductus arteriosus constricts in response to

1. Increased P_{O_2}
2. Decreased P_{CO_2}
3. Increased pH
4. Prostaglandins
    A. 1 only
    B. 2 only
    C. 3 and 4 only
    D. 1 and 4 only

Clinical Application Questions

Case 1

1. During fetal development, the alveolar-capillary system and the quantity of pulmonary surfactant usually are not sufficient to support life until the ______________ week of gestation.

2. As a result of the insufficient amount of pulmonary surfactant, the pathologic processes of a common newborn respiratory disease called ______________ developed.

3. In this case, what are the major anatomic alterations of the lungs associated with the respiratory disease that developed in the infant?

____

____

____

____

____

____

4. Describe the pathophysiology that develops as the conditions listed in question 3 worsen.

____

____

____

5. Describe how the following conditions are manifested in the clinical setting:

Decreased pulmonary diffusion: ______________

____

____

Decreased lung compliance: ______________________

____

____

____

6. Why did PPHN develop in the infant in this case? How did this condition improve?

____

____

____

Case 2

1. Describe why the maternal–placentae–fetal interface was seriously compromised in this case. ______________________

____

____

2. Describe what condition(s) bleeding from the site of maternal–placenta separation may cause to the mother ______________________

____

3. What may develop when the maternal–placenta separation is severe? What procedure must be performed immediately?

____

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CHAPTER 11

Aging and the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the effects of aging on the components of the respiratory system.
2. Explain the impact of aging on arterial blood gases.
3. Describe the effects of aging on the components of the cardiovascular system.

Introduction

The aging process is normal, progressive, and physiologically irreversible. Aging occurs despite optimal nutrition, genetic background, environmental surroundings, and activity patterns. The biological aging process, however, may demonstrate altered rates of progression in response to an individual's genetic background and daily living habits.

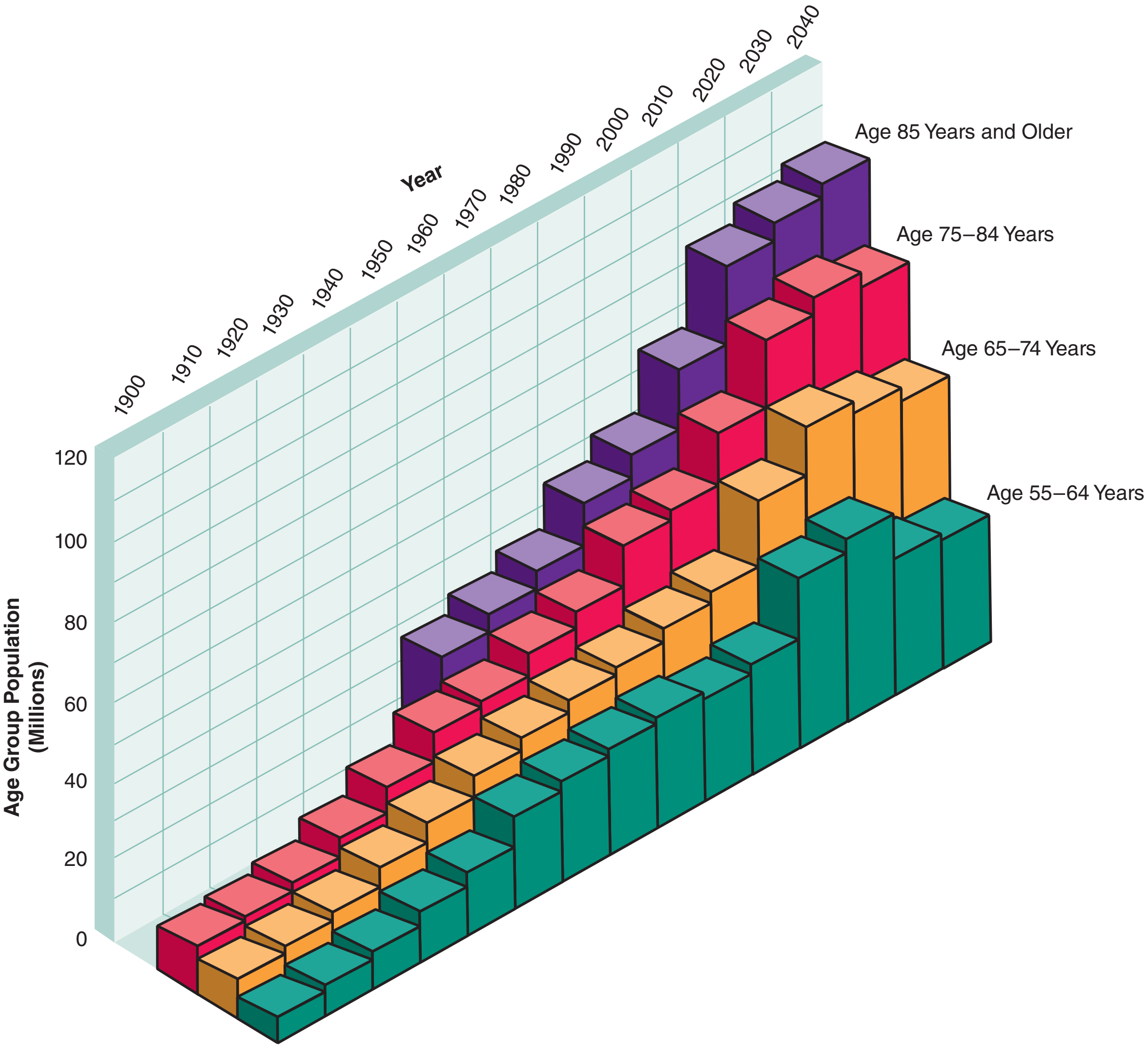
In 2016, the baby boomers—those born between 1946 and 1964—started to turn 70 years old. Presently, there are about 49 million people in the United States who are 65 and older—this number is projected to reach close to 90 million by 2050. Figure 11–1 illustrates the actual and projected population of persons age 55 years and older for four different age groups from 1900 to 2040.

It is also projected that the number of annual short-stay hospital days of persons 65 years and older will increase to about 300,000 by the year 2050 (Figure 11–2). Because the mortality and morbidity rates rise sharply after age 65, the large size of this population will undoubtedly pose a tremendous challenge to the health care industry. A basic understanding of how the aging process affects the cardiopulmonary system is critical for the respiratory therapist.

Effects of Aging on the Respiratory System

The growth and development of the lungs is essentially complete by about 20 years of age. Most of the pulmonary function indices reach their maximum levels between 20 and 25 years of age and then progressively decline. The precise effects of aging on the respiratory system are difficult to determine because the changes associated with time are often indistinguishable from those caused by disease. For example, factors such as long-term exposure to environmental pollutants, recurring pulmonary infections, smoking, and some working conditions can cause alterations in the respiratory system that are not easily differentiated from changes due to aging alone. Despite these difficulties, the conclusions reached here appear to be well founded.

FIGURE 11-1 The actual and projected population of adults age 55 years and older for four different age groups (1900–2040).



Static Mechanical Properties

The **functional residual capacity** is the volume remaining in the lungs when the elastic recoil of the lungs exactly balances the natural tendency of the chest wall to expand. With aging, the elastic recoil of the lungs decreases, causing lung compliance to increase. This is illustrated graphically as a shift to the left (steeper slope) of the volume–pressure curve (Figure 11–3). The decrease in lung elasticity develops because the alveoli progressively deteriorate and enlarge after age 30. Structurally, the alveolar changes resemble the air sac changes associated with emphysema—commonly referred to as **senile emphysema** or **senile hyperinflation of the lungs**.

Even though the potential for greater lung expansion exists as an individual ages, it cannot be realized because of the structural limitations that develop in the chest wall. With aging, the costal cartilages progressively calcify, causing the ribs to slant downward, and this structural change causes the thorax to become less compliant. Because of these anatomic changes, the transpulmonary pressure difference, which is responsible for holding the airways open, is diminished with age.

FIGURE 11-2 The actual and projected annual short-stay hospital days for adults age 65 years and older (1980–2050).

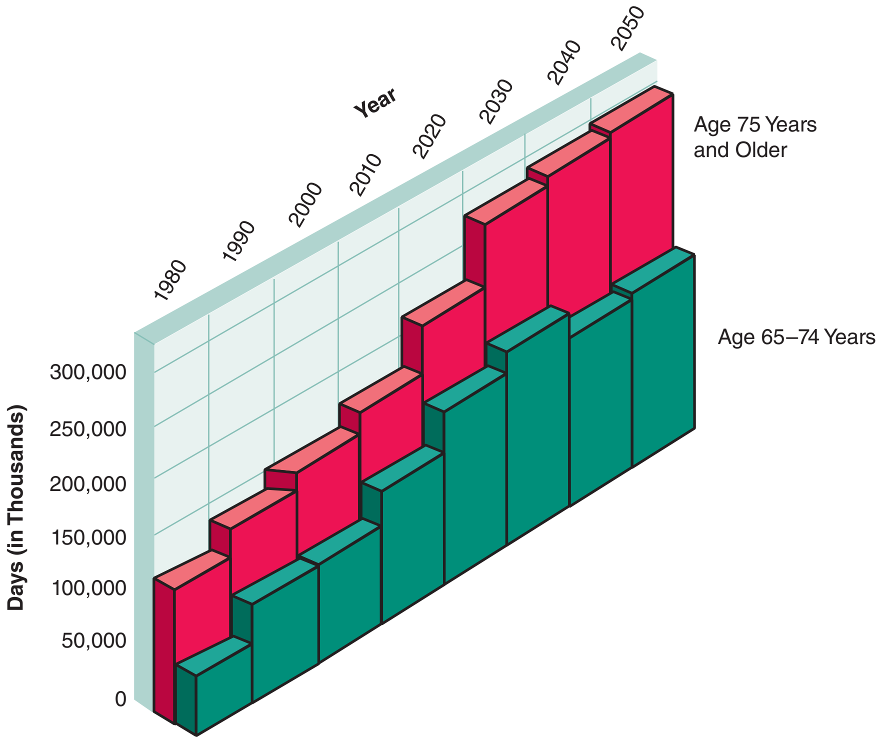
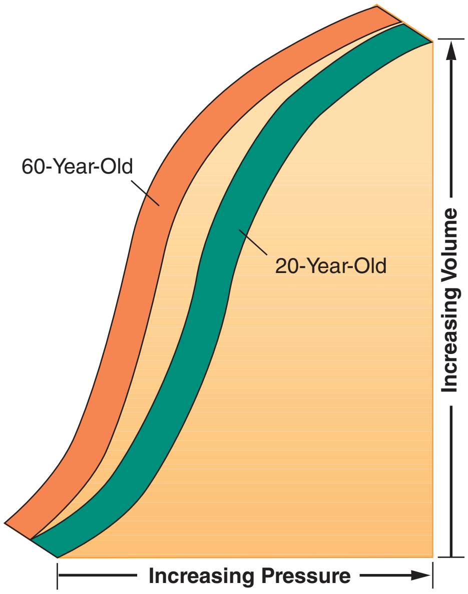


FIGURE 11-3 Comparison of the pressure–volume curve of a 60-year-old adult with that of a 20-year-old adult.



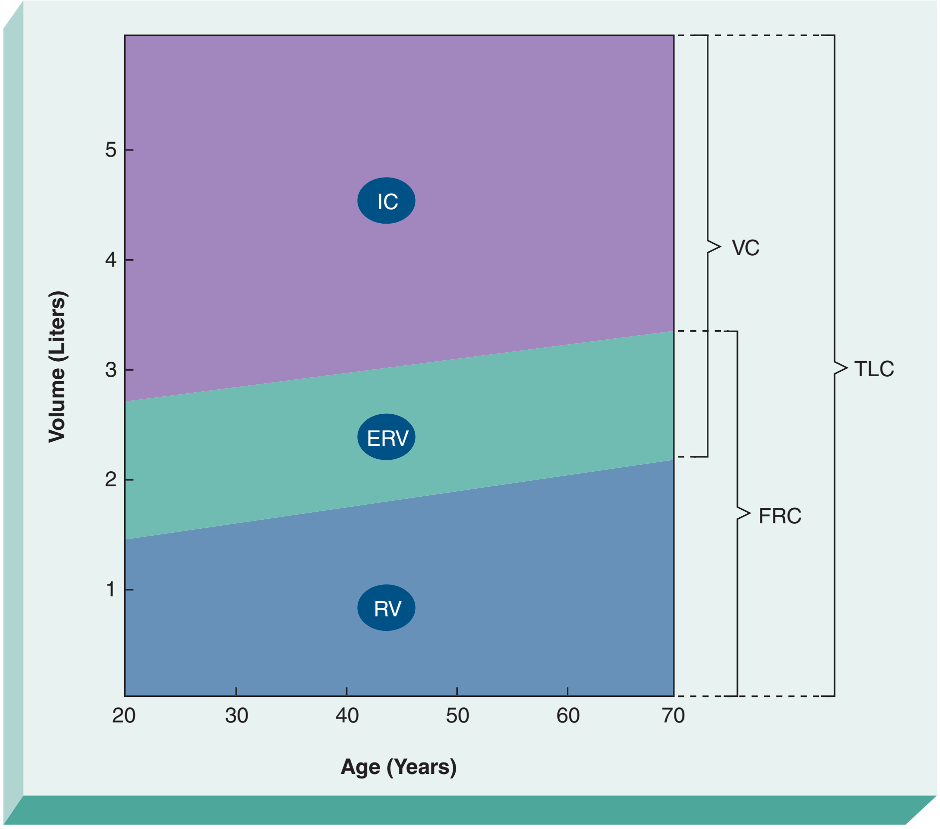
Finally, the reduction in chest wall compliance is slightly greater than the increase in lung compliance, resulting in an overall moderate decline in total compliance of the respiratory system. It is estimated that the work expenditure of a 60-year-old individual to overcome static mechanical forces during normal breathing is 20 percent greater than that of a 20-year-old. The decreased compliance of the respiratory system associated with age is offset by increased respiratory frequency, rather than by increased tidal volume during exertion.

Lung Volumes and Capacities

Figure 11–4 shows the changes that occur in the lung volumes and capacities with aging. Although studies differ, it is generally agreed that the total lung capacity (TLC) essentially remains the same throughout life. Should the TLC decrease, however, it is probably due to the decreased height that typically occurs with age.

It is well documented that the residual volume (RV) increases with age. This is primarily due to age-related alveolar enlargement and to small airway closure. As the RV increases, the RV/TLC ratio also increases. The RV/TLC ratio increases from approximately 20 percent at age 20 to about 35 percent at age 60. This increase occurs predominantly after age 40. Moreover, as the RV increases, the expiratory

FIGURE 11-4 Schematic of the changes that occur in lung volumes and capacities with aging. IC = inspiratory capacity; ERV = expiratory reserve volume; RV = residual volume; VC = vital capacity; FRC = functional residual capacity; TLC = total lung capacity.



reserve volume (ERV) decreases. Most studies show that the functional residual capacity (FRC) increases with age, but not as much as the RV and the RV/TLC. Because the FRC typically increases with age, the inspiratory capacity (IC) decreases.

Because the vital capacity (VC) is equal to the TLC minus the RV, the VC inevitably decreases as the RV increases. It is estimated that in men, the VC decreases about 25 mL/year. In women, the VC decreases about 20 mL/year. In general, the VC decreases about 40 to 50 percent by age 70.

Dynamic Maneuvers of Ventilation

Because of the loss of lung elasticity associated with aging, there is inevitably a marked effect on the dynamics of ventilation. In fact, one of the most prominent physiologic changes associated with age is the reduced efficiency in forced air expulsion. This normal deterioration is reflected by a progressive decrease in the following dynamic lung functions:

- Forced vital capacity (FVC)
- Peak expiratory flow rate (PEFR)
- Forced expiratory flow$_{25–75\%}$ (FEF$_{25–75\%}$)
- Forced expiratory volume in 1 second (FEV$_1$)
- Forced expiratory volume in 1 second/forced vital capacity ratio (FEV$_1$/FVC ratio)
- Maximum voluntary ventilation (MVV)

It is estimated that these dynamic lung functions decrease approximately 20 to 30 percent throughout the average adult's life. For example, it is reported that the FEV$_1$ decreases about 30 mL/year in men and about 20 mL/year in women after about age 20. Initially, the yearly decline in FEV$_1$ is relatively small, but accelerates with age. The FVC decreases about 15 to 30 mL/year in men and 15 to 25 mL/year in women. Precisely what causes the flow rates to decline is still being debated. However, because gas flow is dependent on the applied pressure and the airway resistance, changes in either or both of these factors could be responsible for the reduction of gas flow rates seen in the elderly.

Pulmonary Diffusing Capacity

The pulmonary diffusing capacity (D$_{L_{co}}$) progressively decreases after about 20 years of age. It is estimated that the D$_{L_{co}}$ falls about 20 percent over the course of adult life. In men, it is reported that D$_{L_{co}}$ declines at a rate of about 2 mL/min/mm Hg; in women, the decline is about 1.5 mL/min/mm Hg. This decline results from decreased alveolar surface area caused by alveolar destruction, increased alveolar wall thickness, and decreased pulmonary capillary blood flow—all of which are known to occur with aging.

Alveolar Dead Space Ventilation

Alveolar dead space ventilation increases with advancing age. This is due, in part, to the decreased cardiac index associated with aging and the structural alterations of the pulmonary capillaries that occur as a result of normal alveolar deterioration. In other words, the natural loss of lung elasticity results in an increase in lung compliance, which, in turn, leads to an increase in dead space ventilation. It is estimated that the alveolar dead space ventilation increases about 1 mL/year throughout adult life.

Pulmonary Gas Exchange

The alveolar-arterial oxygen tension difference $P_{(A-a)O_2}$ progressively increases with age. Factors that may increase the $P_{(A-a)O_2}$ include the physiologic shunt, the mismatching of ventilation and perfusion, and a decreased diffusing capacity.

Arterial Blood Gases

In the normal adult, the Pa_{O_2} should be greater than 90 mm Hg up to 45 years of age. After 45 years of age, the Pa_{O_2} generally declines. The minimum low Pa_{O_2}, however, should be greater than 75 mm Hg—regardless of age. Contrary to earlier beliefs, it is now documented that the Pa_{O_2} progressively decreases between the ages of 45 and 75 years and then often increases slightly and levels off.

The Pa_{CO_2} remains constant throughout life. A possible explanation for this is the greater diffusion ability of carbon dioxide through the alveolar-capillary barrier. Because the Pa_{CO_2} remains the same in the healthy older adult, the pH and HCO_3^- levels also remain constant.

Arterial-Venous Oxygen Content Difference

The maximum arterial-venous oxygen content difference $C(a - \bar{v})_{O_2}$ tends to decrease with age. Contributory factors include (1) decline in physical fitness, (2) less efficient peripheral blood distribution, and (3) reduction in tissue enzyme activity.

Hemoglobin Concentration

Anemia is a common finding in the elderly. Several factors predispose the elderly to anemia. Red bone marrow has a tendency to be replaced by fatty marrow, especially in the long bones. Gastrointestinal atrophy, which is commonly associated with advancing age, may slow the absorption of iron or vitamin B_{12}. Gastrointestinal bleeding is also more prevalent in the elderly. Perhaps the most important reasons for anemia in the elderly are sociologic rather than medical—for example, insufficient income to purchase food or decreased interest in cooking and eating adequate meals.

Control of Ventilation

Ventilatory rate and heart rate responses to hypoxia and hypercapnia diminish with age. This is due to a reduced sensitivity and responsiveness of the peripheral and central chemoreceptors and the slowing of central nervous system pathways with age. In addition, age slows the neural output to respiratory muscles and the lower chest wall and reduces lung mechanical efficiency. It is estimated that the ventilatory response to hypoxia is decreased more than 50 percent in the healthy male over 65 years of age; the ventilatory response to hypercapnia is decreased by more than 40 percent. These reductions increase the risk of pulmonary diseases (e.g., pneumonia, chronic obstructive pulmonary disease, and obstructive sleep apnea).

Defense Mechanisms

The rate of the mucociliary transport system declines with age. In addition, there is a decreased cough reflex in more than 70 percent of the elderly population. The decreased cough reflex is caused, in part, by the increased prevalence of medication use (e.g., sedatives) and neurologic diseases associated with the elderly. In addition, dysphagia (impaired esophageal motility), which is commonly seen in the elderly, increases the risk for aspiration and pneumonia.

Exercise Tolerance

In healthy individuals of any age, respiratory function does not limit exercise tolerance. The oxygen transport system is more critically dependent on the cardiovascular system than on respiratory function. The maximal oxygen uptake ($\dot{V}_{O_2max}$), which is the parameter most commonly used to evaluate an individual's aerobic exercise tolerance, peaks at age 20 and progressively and linearly decreases with age. Although there is considerable variation among individuals, it is estimated that from 20 to 60 years of age, a person's maximal oxygen uptake decreases by approximately 35 percent. Evidence indicates, however, that regular physical conditioning throughout life increases oxygen uptake and, therefore, enhances the capacity for exertion during work and recreation.

Pulmonary Diseases in the Elderly

Although the occurrence of pulmonary diseases increases with age, it is difficult to determine the precise relationship aging has to pulmonary disease. This is because aging is also associated with the presence of chronic diseases (e.g., lung cancer, bronchitis, emphysema). It is known, however, that the incidence of serious infectious pulmonary diseases is significantly greater in the elderly. Although the incidence of pneumonia and influenza has decreased dramatically in recent years, pneumonia and influenza are still a major cause of death in the elderly. Evidence suggests that this is partly due to the impaired defense mechanisms in the elderly.

Clinical Connection 11-1

Exercise and Aging

A regular exercise program throughout life can prevent, reduce, or delay some of the common effects associated with aging. There are four main types of exercises that seniors can benefit from:

- **Aerobic activities**—for example, walking, riding a bike, and swimming. These endurance exercises improve the health of the heart and circulatory systems.
- **Muscle strengthening**—for example, free weights or strengthening machines. These activities build muscle tissue and reduce age-related muscle loss.
- **Stretching exercises**—for example, leg, arm, and back stretching activities help to keep the body limber and flexible.
- **Balance exercises**—help to reduce chances of falling.

The accompanying chart provides an overview of some of the well-documented health benefits of exercise.

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(Continued)

Clinical Connection 11-1, Continued

Exercise vs. Aging

	Effects of Aging	Effects of Exercise
Heart and Circulation		
Resting heart rate	Increase	Decrease
Maximum heart rate	Decrease	Slows the decrease
Maximum pumping capacity	Decrease	Increase
Heart muscle stiffness	Increase	Decrease
Blood vessel stiffness	Increase	Decrease
Blood pressure	Increase	Decrease
Risk of heart attack and stroke	Increase	Decrease
Blood		
Number of red blood cells	Decrease	No change
Blood viscosity	Increase	Decrease
Lungs		
Maximum oxygen uptake	Decrease	No change
Intestines		
Speed of emptying	Decrease	Increase
Bones		
Calcium content and strength	Decrease	Increase
Muscles		
Muscle mass and strength	Decrease	Increase
Metabolism		
Metabolic rate	Decrease	Increase
Body fat	Increase	Decrease
Blood sugar	Increase	Decrease
Insulin levels	Increase	Decrease
LDL (“bad”) cholesterol	Increase	Decrease
HDL (“good”) cholesterol	Decrease	Increase
Sex hormone levels	Decrease	Slows decrease
Nervous System		
Quality of sleep	Decrease	Increase
Risk of depression	Increase	Decrease
Memory lapse	Increase	Decrease

Effects of Aging on the Cardiovascular System

A variety of adverse changes develop in the cardiovascular system with age. In fact, the major causes of death in the aging population are diseases of the cardiovascular system. The major changes in the cardiovascular system that develop as a function of age are discussed next.

Structure of the Heart

Between 30 and 80 years of age, the thickness of the left ventricular wall increases by about 25 percent. Cardiac hypertrophy, however, is not considered a primary change associated with aging. In the ventricles, the muscle fiber size progressively increases. Fibrosis develops in the lining of the chambers, and fatty infiltration occurs in the wall of the chambers. The amount of connective tissue increases, causing the heart to become less elastic. Thus, the compliance of the heart is reduced and the heart functions less efficiently as a pump. The heart valves thicken from calcification and fibrosis. This structural change causes the valves to become more rigid and less effective. As the valves become more rigid and distorted, the blood flow may be impeded and systolic murmurs may develop.

Work of the Heart

The work of the heart—defined as Stroke volume × Mean systolic blood pressure—decreases approximately 1 percent per year (Figure 11–5).

Heart Rate

Although the effects of age on the resting heart rate are debated, it is known that the increase in heart rate in response to stress is less in the elderly. The maximum heart rate can be estimated by the following formula:

Maximum heart rate $= 220 - \text{Age}$

Thus, the maximum heart rate for a 60-year-old is about 160 ($220 - 60 = 160$) beats/min. (Recent research has shown that some older subjects can achieve higher heart rates than those predicted by this method.) The reasons for the decreased maximum heart rate are unclear (Figure 11–6). It may be because of the diminished myocardial oxygen supply associated with advanced age. Another possibility is the decreased

FIGURE 11-5 Schematic of the effects of aging on the work of the heart. LVSWI = left ventricular stroke work index.

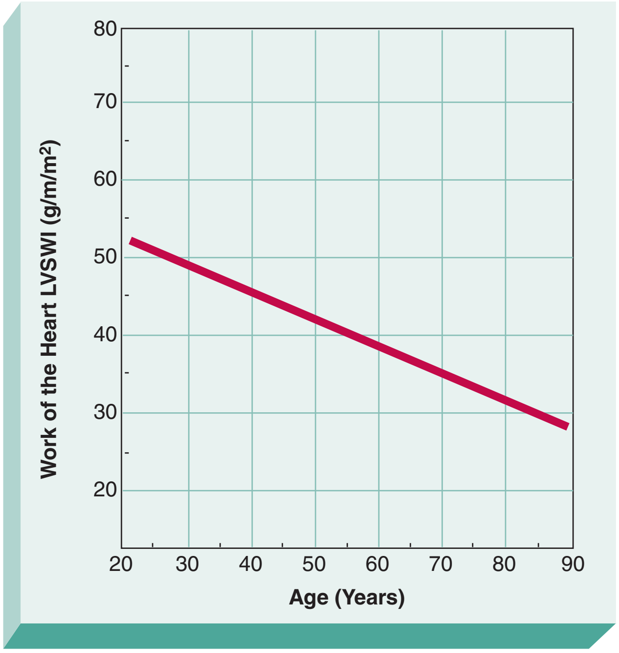
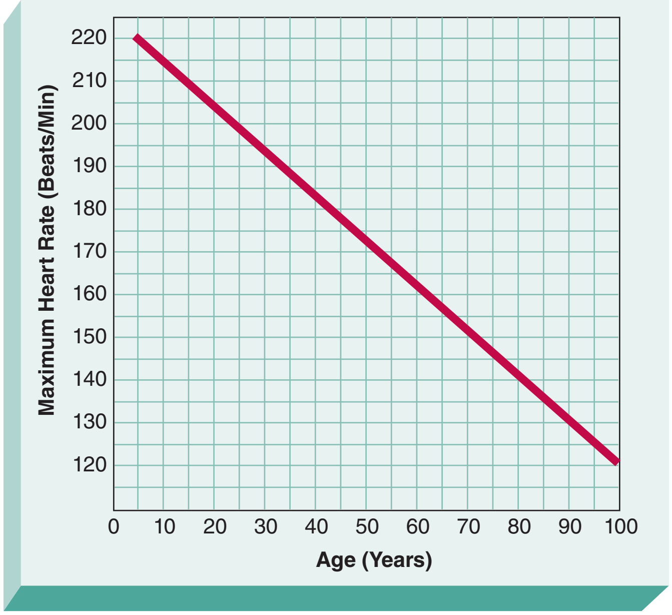


FIGURE 11-6 Schematic of the effects of aging on the maximum heart rate.



compliance of the heart in the elderly. The increase in heart rate in response to stress may be impaired because of increased connective tissue in the sinoatrial and atrioventricular junction and in the bundle branches. The number of catecholamine receptors on the muscle fibers may also be reduced.

With aging, moreover, it not only takes more time for the heart to accelerate, but also takes more time to return to normal after a stressful event. Because of this, the expected increase in pulse rate in response to certain clinical situations (e.g., anxiety, pain, hemorrhage, and infectious processes) is often not as evident in the elderly.

Stroke Volume

The stroke volume diminishes with age. The precise reason for the reduction in the stroke volume is unknown. It is suggested, however, that it may be a reflection of poor myocardial perfusion, decreased cardiac compliance, and poor contractility. As the stroke volume declines, the *stroke volume index* (Stroke volume ÷ Body surface area) also decreases.

Cardiac Output

As the stroke volume diminishes, the cardiac output inevitably declines (Cardiac output = Stroke volume × Heart rate). After age 20, the cardiac output decreases in a linear fashion about 1 percent per year (Figure 11–7). Between the ages of 30 and 80, the cardiac output decreases about 40 percent in both men and women. As the cardiac output declines, the *cardiac index* (Cardiac output ÷ Body surface area) also decreases.

Peripheral Vascular Resistance

It is well documented that the elasticity of the major blood vessels decreases with advancing age. Both the arteries and veins undergo age-related changes. The intima thickens and the media becomes more fibrotic (refer to Figure 1–43). Collagen and extracellular materials accumulate in both the intima and media. As the peripheral vascular system becomes stiffer, its ability to accept the cardiac stroke volume declines. This

FIGURE 11-7 Schematic of the effects of aging on cardiac output.

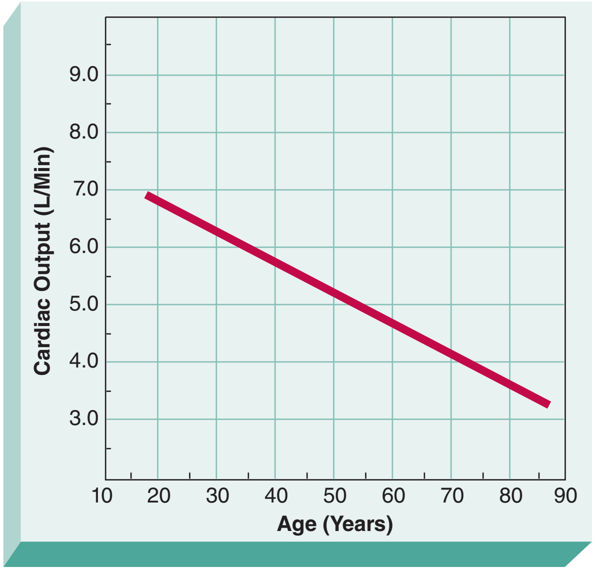
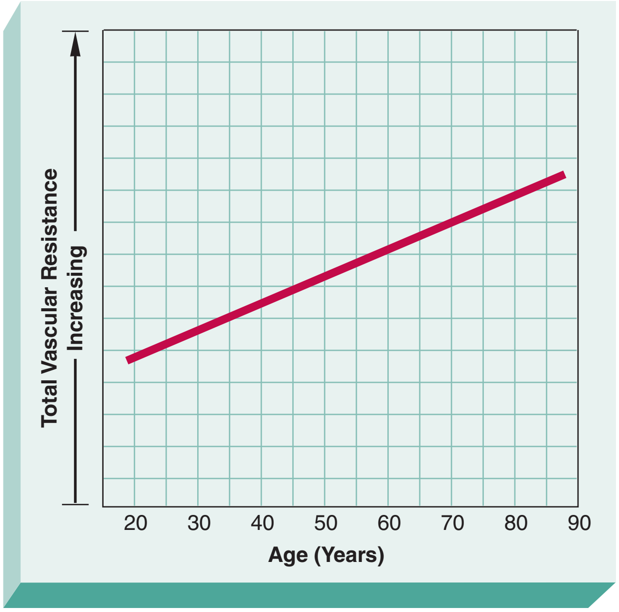


FIGURE 11-8 Schematic of the effects of aging on total peripheral vascular resistance.



age-related development increases the *resting pulse pressure* and the *systolic blood pressure*. It is estimated that the *total* peripheral vascular resistance increases about 1 percent per year (Figure 11–8).

As the peripheral vascular resistance increases, the perfusion of the body organs decreases. This progressive decline in organ perfusion partly explains the many organ debilities seen in elderly people. As the vascular system becomes stiffer with age, its tolerance to change diminishes. For example, a sudden move from the horizontal to the vertical position may cause a marked drop in systemic blood pressure, causing dizziness, confusion, weakness, and fainting. Arterial stiffening also makes the baroreceptors, located in the carotid sinuses and aortic arch, sluggish and less able to moderate blood pressure changes.

Blood Pressure

As described previously, factors associated with aging that increase blood pressure are increasing stiffness of large arteries and increasing total peripheral resistance. Other factors, such as obesity, sodium intake, and stress, can also elevate blood pressure.

Aerobic Capacity

Aerobic capacity decreases about 50 percent between 20 and 80 years of age. This is primarily due to the reduction in muscle mass and strength associated with aging. Other possible causes include the inadequate distribution of blood flow to working muscles and the decreased ability of the tissue cells to extract oxygen.

Clinical Connection 11-2

Aging and Why It Is Never Too Late to Quit Smoking

Respiratory therapists may be faced with patients that continue to smoke despite their diagnosis of COPD. Persistent smokers typically comment like, "Why quit now?" or "At my age, why should I quit?" Is this correct? Is there some age at which it is pointless to quit? In other words, is there an age at which quitting smoking yields no benefit? Or, once the damage from smoking is done, is there no real benefit to quiting, especially in those of advanced age or advanced COPD?

As illustrated in Figure 11–9, long-standing research by C. Fletcher and R. Peto has provided several noteworthy points. First, whether an individual smokes or not, everyone will experience a decline in lung function over the course of their lifetime as related to aging. As previously noted in the text, vital capacity decreases about 20–25 mL/year after adulthood. Because the FEV_1 is a subset of the FVC, it follows that this also decreases as part of the aging process. Note that although the FEV_1 decreases in all individuals past the age of 25, the decline in FEV_1 is accelerated in those individuals who smoke and are susceptible to its effects. The effects of smoking and its subsequent decline in lung function may not be immediately noticeable to the susceptible smoker.

Also note (1) that it is not until lung function deteriorates to approximately 27 percent of the individual's value from age 25 that the effects of disability are documented, and (2) that in nonsmokers and those not susceptible to the effects of smoke (although lung function declines with age), lung function never declines to the level of disability (see Figure 11–9).

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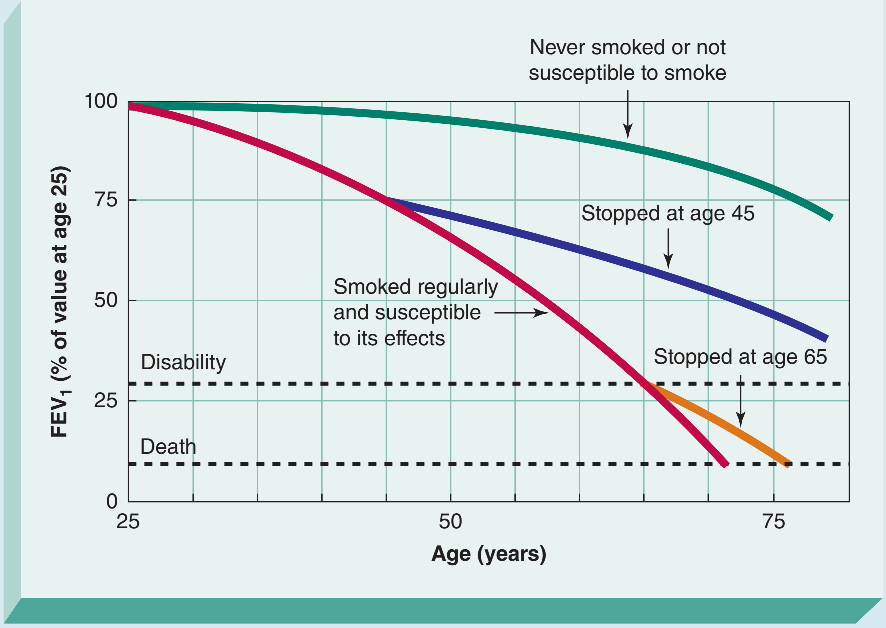
(*Continued*)

Clinical Connection 2-1, Continued

FIGURE 11-9 Lung function in individuals who (1) smoke regularly and who were susceptible to its effects, (2) never smoked or who were not susceptible to smoke, and (3) stop smoking at age 45 or 65.



However, in those individuals who smoke and who are susceptible to smoke, the deterioration in lung function is significantly accelerated to the point of disability (first) and then death. In contrast, stopping smoking is beneficial no matter the age or current level of lung decline. Note that regardless of whether the individual stopped smoking at age 45 or 65, the rate of lung decline slowed to and paralleled the rate of decline of that of a nonsmoker (see Figure 11–9). While lost lung function is not regained, the rate of decline is slowed and slows the onset of disability and death.

Thus, is it ever too late to quit smoking based on age or lung function? The classic research performed by Fletcher and Petro, and summarized in Figure 11–9, strongly supports the concept that all smokers should be strongly encouraged to quit smoking—regardless of their age or pulmonary function status. It is never too late to quit.

Chapter Summary

A fundamental knowledge base of the effects of aging on the cardiopulmonary system is an important part of respiratory care. The major components are the influence of aging on the respiratory system, including the static mechanical properties of the lungs, lung volumes and capacities, dynamic maneuvers of ventilation, pulmonary diffusing capacity, and alveolar dead space ventilation, as well as pulmonary gas exchange, arterial blood gases, arterial-venous oxygen content difference, hemoglobin concentration, control of ventilation, defense mechanisms, exercise tolerance, and presence of pulmonary diseases. The knowledge base should also include the effects of aging on the cardiovascular system, including the structure of the heart, work of the heart, heart rate, stroke volume, cardiac output, peripheral vascular resistance, blood pressure, and aerobic capacity. Clinical connections associated with the preceding topics include (1) exercise and aging and (2) why it is never too late to quit smoking.

Review Questions

1. As an individual ages, the
   - A. Residual volume decreases
   - B. Expiratory reserve volume increases
   - C. Functional residual capacity decreases
   - D. Vital capacity decreases

2. Most of the lung function indices reach their maximum levels between
   - A. 5–10 years of age
   - B. 10–15 years of age
   - C. 15–20 years of age
   - D. 20–25 years of age

3. With advancing age, the
   1. Lung compliance decreases
   2. Chest wall compliance increases
   3. Lung compliance increases
   4. Chest wall compliance decreases
      - A. 2 only
      - B. 3 only
      - C. 1 and 2 only
      - D. 3 and 4 only

4. As an individual ages, the
   1. Forced vital capacity increases
   2. Peak expiratory flow rate decreases
   3. Forced expiratory volume in 1 second increases
   4. Maximum voluntary ventilation increases
      - A. 1 only
      - B. 2 only
      - C. 2 and 4 only
      - D. 3 and 4 only

5. With advancing age, the
   1. Pa_{CO_2} increases
   2. Pa_{O_2} decreases
   3. $P_{(A-a)O_2}$ decreases
   4. $C(a - \bar{v})_{O_2}$ decreases
      - A. 1 only
      - B. 2 only
      - C. 3 and 4 only
      - D. 2 and 4 only

6. The maximum heart rate of a 45-year-old person is
   - A. 155 beats/min
   - B. 165 beats/min
   - C. 175 beats/min
   - D. 185 beats/min

7. Over the course of life, the diffusion capacity decreases by about
   - A. 5 percent
   - B. 10 percent
   - C. 15 percent
   - D. 20 percent

8. Between 30 and 80 years of age, the cardiac output decreases by about
   - A. 10 percent
   - B. 20 percent
   - C. 30 percent
   - D. 40 percent

9. With advancing age, the
   1. Blood pressure increases
   2. Stroke volume decreases
   3. Cardiac output increases
   4. Heart work decreases
      - A. 1 only
      - B. 2 only
      - C. 3 and 4 only
      - D. 1, 2, and 4 only

10. Between 20 and 60 years of age, the RV/TLC ratio
   - A. Increases from 20 to 25 percent
   - B. Increases from 20 to 30 percent
   - C. Increases from 20 to 35 percent
   - D. Increases from 20 to 40 percent

SECTION

2

Advanced Cardiopulmonary Concepts and Related Areas

The Essentials

CHAPTER 12
Electrophysiology of the Heart

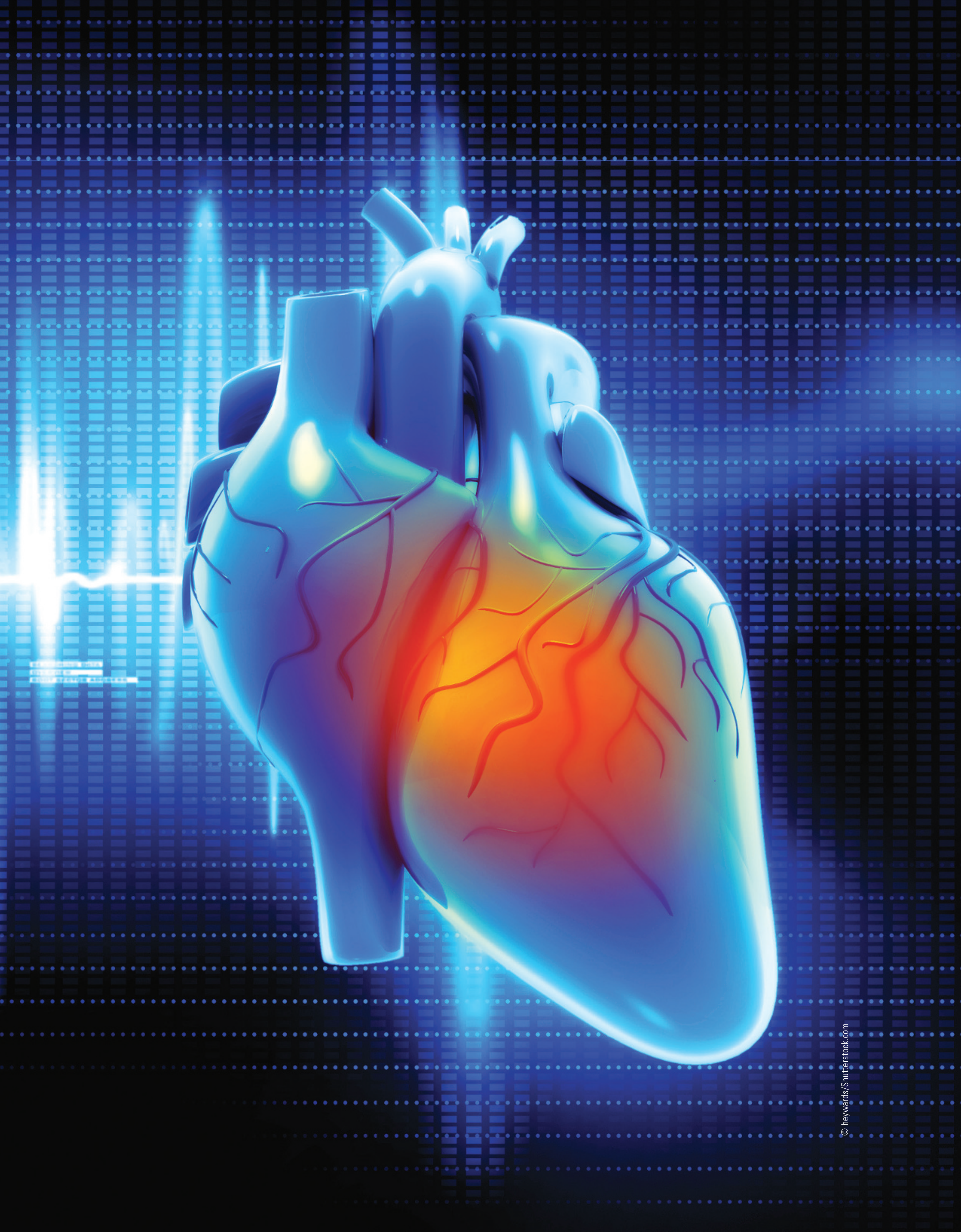
CHAPTER 13
The Standard 12-ECG Lead System

CHAPTER 14
ECG Interpretation

CHAPTER 15
Hemodynamic Measurements

CHAPTER 16
Renal Failure and Its Effects on the Cardiopulmonary System

CHAPTER 17
Sleep Physiology and Its Relationship to the Cardiopulmonary System



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CHAPTER 12

Electrophysiology of the Heart

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the electrophysiology of the heart, including action potential and phases 1 through 4.
2. Describe the properties of the cardiac muscle, including automaticity, excitability, conductivity, and contractility.
3. Explain the refractory periods of the heart.
4. Identify the major components of the conductive system of the heart.
5. Describe the cardiac effects of the sympathetic nervous system and the parasympathetic nervous system

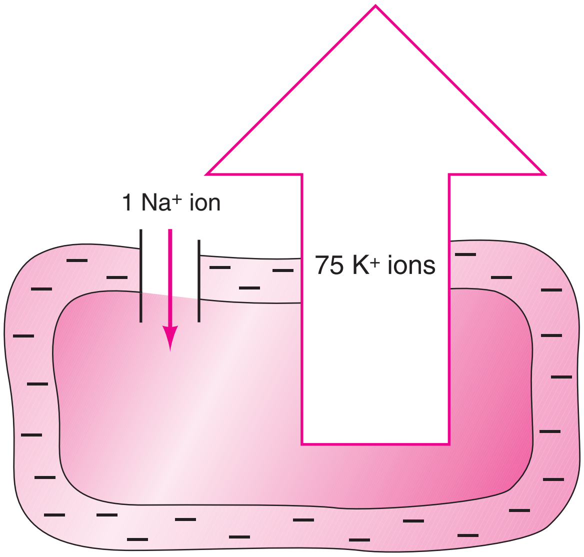
Introduction

The heart contracts by generating and propagating **action potentials**, which are electrical currents that travel across the cell membranes of the heart. The electrical events of an action potential are identical in skeletal muscles, cardiac muscle, and neurons. In neurons, however, a transmitted action potential is called a **nerve impulse**. When the heart is relaxed (i.e., not generating an action potential), the cardiac muscle fibers are in what is called their **polarized** or **resting state**. During this period, there is an electrical charge difference across the fibers of the heart cells. This electrical difference between the electrolytes inside the cell membranes and the electrolytes outside of the cell membranes is called the **resting membrane potential (RMP)**.

The primary electrolytes responsible for the electrical difference across the RMP are **potassium (K^+)**, **sodium (Na^+)**, and **calcium (Ca^{2+})**. Similar to all the cells in the body, the concentration of K^+ is greatest inside the cardiac cell—about 151 mEq/L—and the concentration of K^+ outside the cardiac cell is about 4 mEq/L. For Na^+ and Ca^{2+}, the opposite is true. The concentration of Na^+ outside the cardiac cell is about 144 mEq/L and about 7 mEq/L inside the cell; the concentration of Ca^{2+} is about 5 mEq/L outside the cell and less than 1 mEq/L inside the cell.

When the cardiac cell is in its resting or polarized state, the inside of the cell is negatively charged with the K^+ cation, and the outside of the cell is positively charged with the Na^+ cation. The way in which this relationship (i.e., negative inside the cell and positive outside of the cell) develops with two cations (positive ions) is as follows: In the polarized state, the Na^+/K^+ pump establishes (1) an increased Na^+ concentration outside of the cell and (2) an increased K^+ concentration inside of the cell. Both ions then diffuse along their concentration gradients; that is, K^+ diffuses out of the cell while, at the same time, Na^+ diffuses

FIGURE 12-1 The polarized state. For each Na^+ ion that diffuses into the cell, about 75 K^+ ions diffuse out of the cell. The result is a deficiency of positive cations inside the cell; this is a cell with a negative charge.



into the cell. For every 50 to 75 K^+ ions that diffuse out of the cell, only 1 Na^+ diffuses into the cell. This exchange ratio results in a deficiency of positive cations inside the cell; that is, an electrical difference (RMP) between the electrolytes inside the cell and the electrolytes outside the cell is generated (Figure 12–1).

The potential force of the RMP is measured in millivolts (mV) (1 mV = 0.001 V). The RMP of the myocardial cells is about −90 mV. The cornerstone to the understanding of the electrophysiology of the heart is the five electrophysiologic phases of the action potential. An electrocardiogram (ECG) is used to record the five phases of the action potential. A variety of heart abnormalities can disrupt any of these five electrophysiologic phases and, therefore, disrupt and alter the configuration of a normal ECG tracing.

Five Phases of the Action Potential

Depolarization

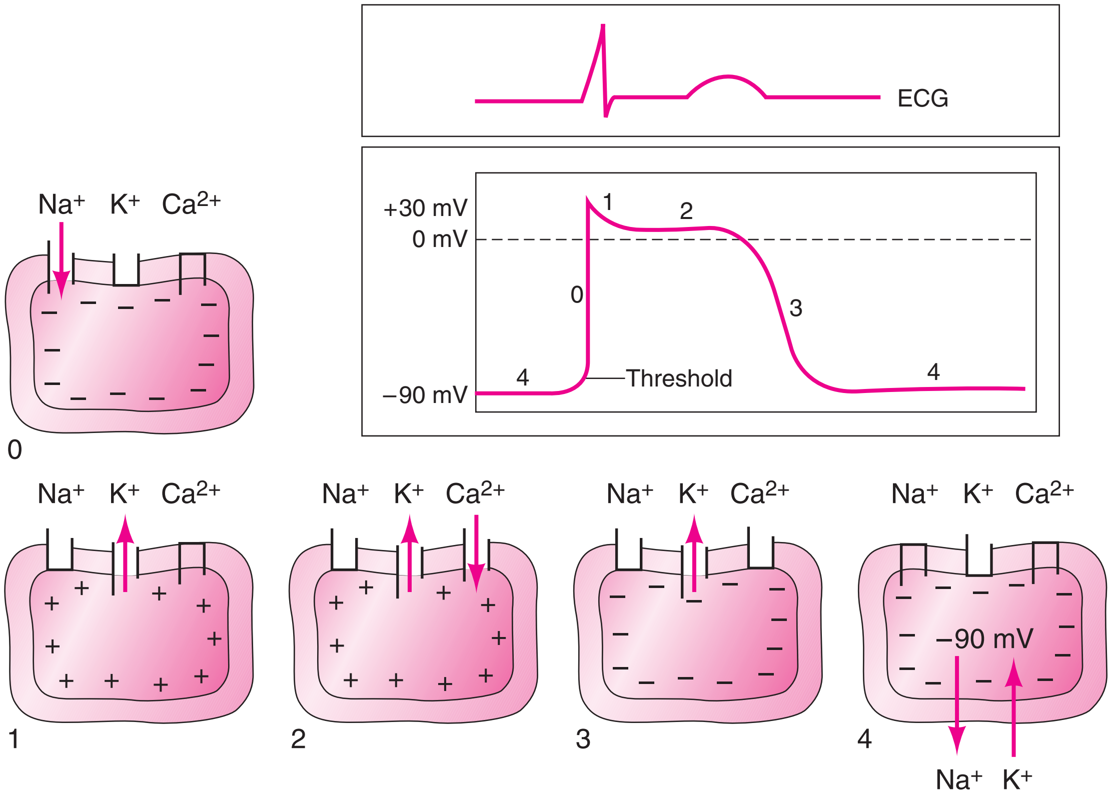
Depolarization is the trigger for myocardial contraction.

Phase 0: **Rapid depolarization (early phase).** Under normal conditions, the ventricular muscle fibers are activated between 60 and 100 times/min by an electrical impulse initiated by the sinoatrial (SA) node. This action changes the RMP and allows a rapid inward flow of Na^+ into the cell through specific Na^+ channels. This process causes the inside of the cell to become positively charged. The voltage inside the cell at the end of depolarization is about +30 mV. This electrophysiologic event produces a rapid upstroke in the action potential (see Figure 12–2).

Repolarization

Repolarization is the process by which the cells of the heart return to their resting state.

FIGURE 12-2 The action potential and the Na^+, K^+, and Ca^{2+} changes during phases 0, 1, 2, 3, and 4.



Phase 1: **Initial repolarization**. Immediately after phase 0, the channels for K^+ open and permit K^+ to flow out of the cell, an action that produces an early, but incomplete, repolarization (repolarization is slowed by the phase 2 influx of Ca^{2+} ions). Phase 1 is illustrated as a short downward stroke in the action potential curve just before the plateau (see Figure 12–2).

Phase 2: **Plateau state**. During this period, there is slow inward flow of Ca^{2+}, which, in turn, significantly slows the outward flow of K^+. The plateau phase prolongs the contraction of the myocardial cells (see Figure 12–2).

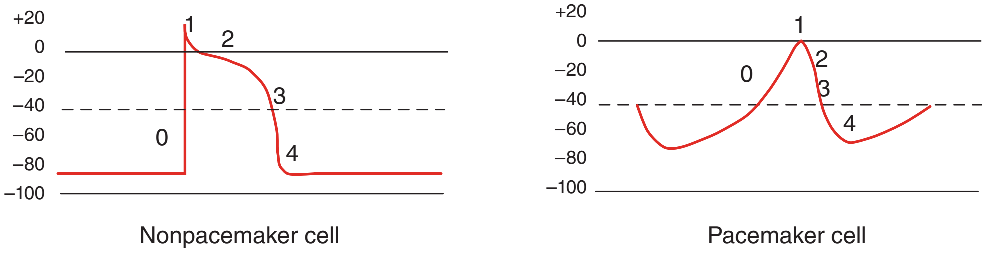
Phase 3: **Final rapid repolarization**. During this period, the inward flow of Ca^{2+} stops, the outward flow of K^+ is again accelerated, and the rate of repolarization accelerates (see Figure 12–2).

Phase 4: **Resting or polarized state**. During this period, the voltage-sensitive ion channels return to their pre-depolarization permeability. The excess Na^+ inside the cell (that occurred during depolarization) and the loss of K^+ (that occurred during repolarization) are returned to normal by the Na^+ and K^+ ion pumps. An additional Na^+ and Ca^{2+} pump removes the excess of Ca^{2+} from the cell (see Figure 12–2).

Properties of the Cardiac Muscle

The heart is composed of two types of cardiac cells: **contractile muscle fibers** and specialized "pacemaker cells" called **autorhythmic cells**. The myocardial contractile fiber cells make up the bulk of the musculature of the myocardium and are responsible for the pumping activity of the heart. Approximately 1 percent of

FIGURE 12-3 Schematic comparing action potential of pacemaker and nonpacemaker (working) myocardial cells.



the heart is composed of the autorhythmic cells, the majority of which are located in the SA node. These cells have the unique ability to initiate an action potential spontaneously, which, in turn, triggers the myocardial fibers to contract. The cardiac cells of the heart have four specific properties: automaticity, excitability, conductivity, and contractility.

- **Automaticity** is the unique ability of the cells in the SA node (pacemaker cells) to generate an action potential without being stimulated. This occurs because the cell membranes of the pacemaker cells permit Na^+ to leak into the cell during phase 4. As Na^+ enters the cell, the RMP slowly increases. When the threshold potential (TP) of the pacemaker cells is reached (between –40 and –60 mV), the cells of the SA node rapidly depolarize (Figure 12–3). Under normal conditions, the unique automaticity of the pacemaker cells stimulates the action potential of the heart's conductive system (i.e., atria, atrioventricular [AV] junction, bundle branches, Purkinje fibers, ventricles) at regular and usually predictable intervals (Figure 12–4).
- **Excitability** (irritability) is the ability of a cell to reach its threshold potential and respond to a stimulus or irritation. The lower the stimulus needed to activate a cell, the more excitable the cell; conversely, the greater the stimulus needed, the less excitable the cell. The presence of ischemia and hypoxia causes the myocardial cell to become more excitable.
- **Conductivity** is the unique ability of the heart cells to transmit electrical current from cell to cell throughout the entire conductive system.
- **Contractility** is the ability of cardiac muscle fibers to shorten and contract in response to an electrical stimulus.

Refractory Periods

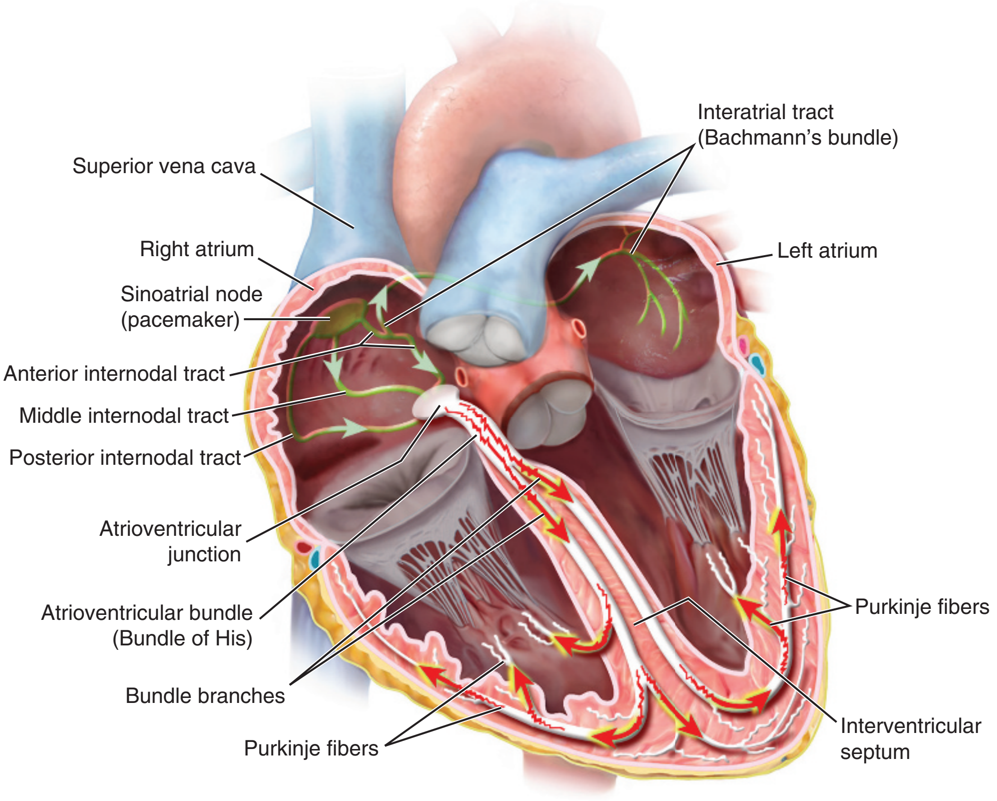
Additional properties of the myocardial contractile fibers and autorhythmic cells are refractory periods, which entail (1) the ionic composition of the cells during different phases of the action potential and (2) the ability of the cells to accept a stimulus.

The **absolute refractory period** is the time in which the cells cannot respond to a stimulus. The ionic composition of the cells is not in place to receive a stimulus. Phases 0, 1, 2, and about half of phase 3 represent the absolute refractory period (see Figure 12–2).

The **relative refractory period** is the time in which repolarization is almost complete and where a strong stimulus may cause depolarization of some of the cells. Some cells may respond normally, some in an abnormal way, and some not at all. The second half of phase 3 represents the relative refractory period of the action potential (see Figure 12–2).

The **nonrefractory period** occurs when all the cells are in their resting or polarized state. The cells are ready to respond to a stimulus in a normal fashion. Phase 4 represents the nonrefractory period (see Figure 12–2).

FIGURE 12-4 Conductive system of the heart.


Superior vena cava
Right atrium
Sinoatrial node (pacemaker)
Anterior internodal tract
Middle internodal tract
Posterior internodal tract
Atrioventricular junction
Atrioventricular bundle (Bundle of His)
Bundle branches
Purkinje fibers
Interatrial tract (Bachmann's bundle)
Left atrium
Purkinje fibers
Interventricular septum

The duration of each refractory period may vary in response to use of medications or recreational drugs, or presence of disease, electrolyte imbalance, myocardial ischemia, or myocardial injury.

The Conductive System

As shown in Figure 12–4, the components of the conductive system include the **sinoatrial node** (SA node), **atrioventricular junction** (AV junction), **bundle of His**, the **right** and **left bundle branches**, and the **Purkinje fibers**. The electrical cycle of the heart begins with the SA node, or pacemaker. The SA node initiates the cardiac contraction by producing an electrical impulse that travels through the right and left atria. In the right atrium, the electrical impulse is conducted through the **anterior internodal tract, middle internodal tract**, and **posterior internodal tract**. All three internodal pathways become one at the AV junction. The **Bachmann's bundle** conducts electrical impulses from the SA node directly to the left atrium. The electrical impulse generated by the SA node causes the right and left atria to contract simultaneously. This action, in turn, forces the blood in the atria to move into the ventricles.

The AV junction is located just behind the tricuspid in the lower portion of the right interatrial septum. The AV junction relays the electrical impulse from the atria to the ventricles via the bundle of His (also called the AV bundle). The bundle of His enters the intraventricular septum and divides into the left and right bundle branches. At the heart's apex, the Purkinje fibers spread throughout the posterior portion of the ventricle and head back toward the base of the heart. In the normal heart, the total time required for an electrical impulse to travel from the SA node to the end of the Purkinje fibers is about 0.22 second. In other words, the entire heart depolarizes in about 0.22 second.

Autonomic Nervous System

Even though the conductive system of the heart has its own intrinsic pacemaker, the autonomic nervous system plays an important role in the rate of impulse formation, conduction, and contraction strength. The regulation of the heart is controlled by neural fibers from both the sympathetic and parasympathetic nervous systems.

Sympathetic neural fibers innervate the atria and ventricles of the heart. When stimulated, the sympathetic fibers cause an *increase* in the heart rate, AV conduction, cardiac contractility, and excitability. **Parasympathetic** neural fibers, via the vagus nerve, innervate the SA node, atrial muscle fibers, and the AV junction. The parasympathetic system has little or no influence on the ventricular musculature. Stimulation of the parasympathetic system causes a *decrease* in heart rate, AV conduction, contractility, and excitability.

Under normal circumstances, the heart action is maintained in a state of balanced control because of the opposing effects of the sympathetic and parasympathetic systems. However, a variety of dysrhythmias can develop when the autonomic nervous system is influenced by medications or abnormal conditions. When the sympathetic nervous system is stimulated by a drug (e.g., epinephrine), the heart rate will increase. On the other hand, when a drug (i.e., propranol) blocks the sympathetic nervous system, the parasympathetic nervous system takes control and the heart rate decreases. Table 12–1 summarizes cardiac response to autonomic nervous system changes.

Clinical Connection 12-1

Synchronized Cardioversion Defibrillation versus Unsynchronized Cardioversion Defibrillation

Synchronized cardioversion defibrillation is a low-energy shock that is synchronized with the peak of the QRS complex (ventricular depolarization). When the "sync" option is engaged on a defibrillator and the shock button is pushed, there will be a delay in the shock until the defibrillator reads and synchronizes the shock with the patient's ECG rhythm—the peak of the R-wave in the patient's QRS complex. A synchronized cardioversion avoids shocking the patient's heart during the repolarization phase. Common indications for synchronized cardioversion include unstable atrial fibrillation, atrial flutter, atrial tachycardia, and supraventricular tachycardia.

Unsynchronized cardioversion defibrillation is a high-energy shock that is delivered as soon as the shock button is pushed on the defibrillator. The electrical current may fall randomly anywhere within the cardiac cycle—the QRS complex. An unsynchronized cardioversion is used when there is no coordinated electrical heart activity—a pulseless ventricular tachycardia or ventricular fibrillation—or when the defibrillator fails to synchronize with the electrical activity of the heart in an unstable patient.

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TABLE 12-1 Cardiac Response to Autonomic Nervous System Changes

Sympathetic Stimulation	Sympathetic Block	Parasympathetic Stimulation	Parasympathetic Block
↑ Heart rate	↓ Heart rate	↓ Heart rate	↑ Heart rate

Chapter Summary

Cardiac contractions are a function of action potentials (electrical currents) that sweep across the cell membranes of the heart. Each action potential consists of five phases: phases 0, 1, 2, 3, and 4. Phase 0 represents depolarization, and phases 1, 2, 3, and 4 represent different stages of repolarization. The cardiac cells of the heart have four specific properties: automaticity, excitability, conductivity, and contractility. Automaticity is the unique ability of the cells in the sinoatrial (SA) node (pacemaker cells) to generate an action potential without being stimulated. Excitability (irritability) is the ability of a cell to reach its threshold potential and respond to a stimulus or irritation. Conductivity is the ability of the heart cells to transmit electrical current from cell to cell throughout the entire conductive system. Contractility is the ability of cardiac muscle fibers to shorten and contract in response to an electrical stimulus.

An additional property of the myocardial contractile fibers and autorhythmic cells is refractory periods, which include (1) the ionic composition of the cells during different phases of the action potential and (2) the ability of the cells to accept a stimulus. The absolute refractory period is the phase in which the cells cannot respond to a stimulus. The relative refractory period is the time in which repolarization is partially complete and a strong stimulus may cause depolarization of some of the cell. The nonrefractory period is when all the cells are in their resting or polarized state and are ready to respond to a stimulus in a normal fashion.

The components of the conductive system are the sinoatrial node (SA node), atrioventricular junction (AV junction), bundle of His, the right and left bundle branches, and the Purkinje fibers. Finally, although the conductive system of the heart has its own intrinsic pacemaker, the autonomic nervous system plays an important role in the rate of impulse formation, conduction, and contraction strength. The regulation of the heart is controlled by neural fibers from both the sympathetic and parasympathetic nervous systems. A clinical connection associated with the preceding topics discusses synchronized cardioversion defibrillation versus unsynchronized cardioversion defibrillation.

Review Questions

1. Which of the following is the rapid upstroke in the action potential?

A. Phase 0
B. Phase 1
C. Phase 2
D. Phase 3

2. When does the inward flow of Ca^{2+} into the heart stop?

A. Phase 1
B. Phase 2
C. Phase 3
D. Phase 4

3. Which of the following is the plateau stage of the action potential?
A. Phase 0
B. Phase 1
C. Phase 2
D. Phase 3

4. The sinoatrial node is also called the
A. Pacemaker
B. Action potential
C. Resting membrane potential
D. Relative refractory period

5. Which of the following slows the heart rate and AV conduction?
A. Resting membrane potential
B. Parasympathetic nervous system
C. Pacemaker
D. Phase 0

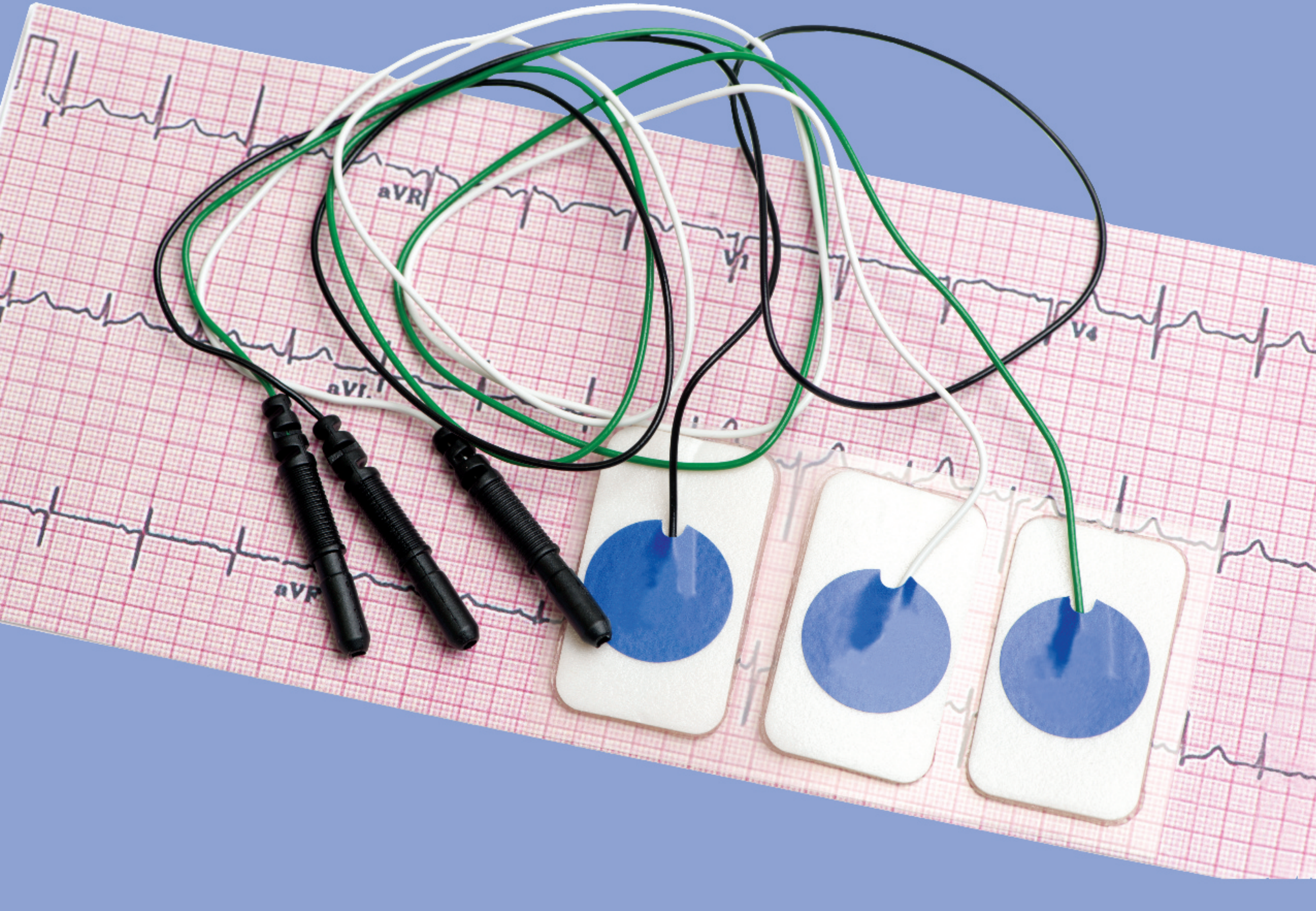
6. When can a strong stimulus cause an unwanted depolarization of the heart?
A. Absolute refractory period
B. Relative refractory period
C. Nonrefractory period
D. Phase 0

7. Which of the following is called the resting state?
A. Phase 1
B. Phase 2
C. Phase 3
D. Phase 4

8. Which of the following means the ability to transmit electrical current from one cell to another?
A. Conductivity
B. Excitability
C. Contractility
D. Automaticity

9. An electrical difference across the fibers of the heart is called the
A. Absolute refractory period
B. Resting membrane potential
C. Action potential
D. Depolarization

10. The entire sequence of electrical changes during depolarization and repolarization is called
A. Nonrefractory period
B. Conductivity
C. Contractility
D. Action potential


aVR
V1
V4
aVL
aVR

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CHAPTER 13

The Standard 12-ECG Lead System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the components of the standard limb leads.
2. Describe how an electrical impulse of the heart is recorded when it moves toward a positive electrode, moves away from a positive electrode, and moves perpendicular to a positive and negative electrode.
3. Identify how the left lateral leads and inferior leads monitor the frontal plane of the heart.
4. Describe the components of the precordial (chest) leads.
5. Identify how precordial leads monitor the horizontal plane of the heart.
6. Describe the modified chest lead.
7. Explain the normal electrocardiogram (ECG) configurations and their expected measurements.

Introduction

The electrocardiogram (ECG) is a graphic representation of the electrical activity of the heart's conductive system recorded over a period of time. Under normal conditions, ECG tracings have very predictable directions, durations, and amplitudes. Because of this fact, the various components of the ECG tracing can be identified, assessed, and interpreted as to normal or abnormal function. The ECG is also used to monitor the heart's response to therapeutic interventions. Because the ECG is such a useful tool in the clinical setting, the respiratory therapist must have a basic and appropriate understanding of ECG analysis. The essential knowledge components required for a systematic 12-ECG interpretation are discussed.

The Standard 12-ECG Lead System

The standard 12-ECG lead system consists of four limb electrodes and six chest electrodes. Collectively, the electrodes (or leads) view the electrical activity of the heart from 12 different positions—six *standard limb leads* and six *precordial (chest) leads* (Table 13–1). Each lead (1) views the electrical activity of the heart from a different angle, (2) has a positive and negative component, and (3) monitors specific portions of the heart from the point of view of the positive electrode in that lead.

TABLE 13-1 ECG Lead Systems

Standard Limb Leads		Precordial (Chest) Leads
Bipolar Leads	**Unipolar Leads**	**Unipolar Leads**
Lead I	aVR	V1
Lead II	aVL	V2
Lead III	aVF	V3
		V4
		V5
		V6

Standard Limb Leads

As shown in Figure 13–1, the *standard limb leads* are **leads I**, **II**, **III**, **aVR**, **aVL**, and **aVF**. They are called the limb leads because they are derived from electrodes attached to the arms and legs. Leads I, II, and III are **bipolar leads**, which means they use two electrodes to monitor the heart, one positive and one negative. As illustrated in Figure 13–2, an imaginary line can be drawn between the positive and negative electrodes for leads I, II, and III. These lines represent the **axis** of each lead. The triangle formed around the heart by the three axes is called *Einthoven's triangle*.

Electrical impulses that travel more toward the positive electrode (relative to the axis of the lead) are recorded as positive deflections in that lead (see lead I, Figure 13–3A). When an electrical current travels perpendicular to the lead axis, an equiphasic (half up and half down deflection) or a straight line is recorded (see lead II, Figure 13–3B). Electrical impulses that move away from the positive electrode (or more toward the negative electrode) are recorded as negative deflections in that lead (see lead III, Figure 13–3C). In the normal heart, the largest electrical impulse travels from the base of the heart to the apex, in a right to left direction (Figure 13–4).

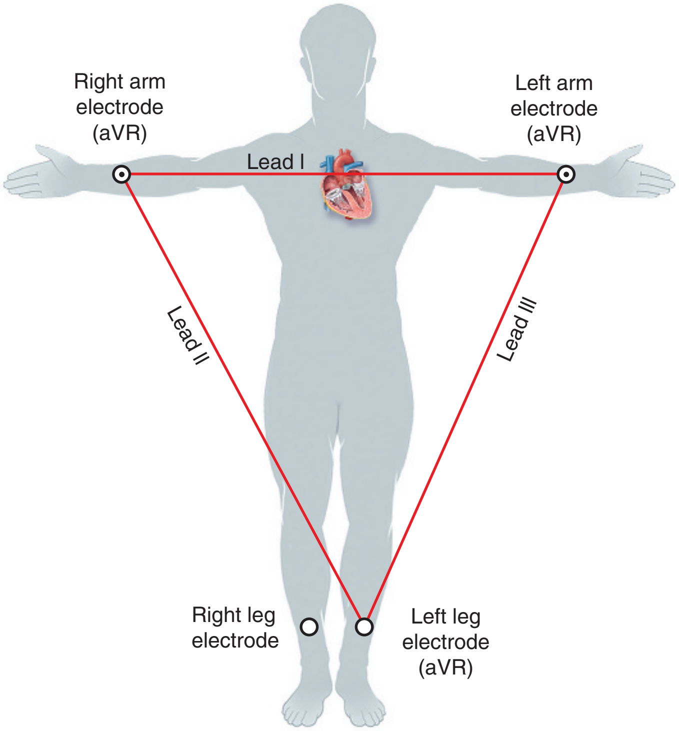
The aVR, aVL, and aVF leads are **unipolar leads** (see Figure 13–1). Unipolar leads monitor the electrical activity of the heart between the positive electrode (i.e., aVR, aVL, aVF) and the zero-electrical reference point at the center of the heart. In essence, the center of the heart functions as a negative electrode. Thus, the axis for these leads is drawn from the electrode and the center of the heart. When the negative electrodes are eliminated in the aVR, aVL, and aVF, the amplitude of the ECG recordings is augmented by 50 percent. This is the reason for the letter a, which stands for augmentation; the *V* represents voltage. The letters *R, L,* and *F* represent where the positive electrode is placed.

Collectively, the limb leads monitor the electrical activity of the heart in the **frontal plane**, which is the electrical activity that flows over the anterior surface of the heart; from the **base to the apex of the heart**, in a **right to left** direction. Leads I and aVL are called **left lateral leads** because they monitor the left lateral side of the heart. Leads II, III, and aVF view the lower surfaces of the heart and are called **inferior leads**. The aVR lead does not contribute much information for the 12-ECG interpretation and because of this fact, it is generally ignored. Figure 13–5 summarizes the frontal plane and the limb leads.

Precordial (Chest) Leads

Figure 13–6 shows the chest position of the *precordial leads,* which are also unipolar leads (i.e., the center of the heart functions as the negative reference point, similar to the aVR, aVL, and aVF leads). Figure 13–7 shows the axes of the six precordial leads. The precordial leads monitor the heart from the **horizontal plane**,

FIGURE 13-1 The standard limb leads—leads I, II, III, aVR, aVL, and aVF. Each of the standard limb electrodes can function as either a positive or negative electrode.


Right arm electrode (aVR)
Left arm electrode (aVR)
Lead I
Lead II
Lead III
Right leg electrode
Left leg electrode (aVR)

Lead	Right arm	Right leg	Left leg	Left arm
I	–			+
II	–		+	
III			+	–
aVR	+	–	–	–
aVL	–	–	–	+
aVF	–	–	+	–

which means they record electrical activity that transverses the heart. Leads V1 and V2 monitor the right ventricle, V3 and V4 monitor the ventricular septum, and V5 and V6 view the left ventricle. Leads V1, V2, V3, and V4 are also called **anterior leads**, and leads V5 and V6 are also called **lateral leads**. Figure 13–8 summarizes the horizontal plane and its leads.

Modified Chest Lead

The *modified chest lead* (MCL$_1$) is a bipolar chest lead similar to the precordial lead V1. The positive electrode is placed on the chest (in the same position as V1) and the negative electrode is placed on the left arm or left shoulder area (Figure 13–9). The MCL$_1$ may be helpful in visualizing some waveforms.

FIGURE 13-2 Leads I, II, and III axes form Einthoven's triangle.

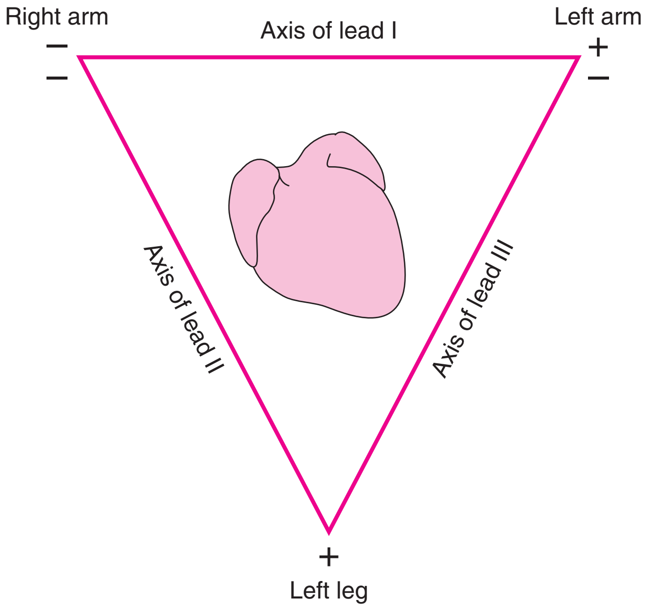

Right arm
−
−
Axis of lead I
Left arm
+
−
Axis of lead II
Axis of lead III
+
Left leg

FIGURE 13-3 Einthoven's triangle around the heart. The arrow represents an electrical impulse moving across the surface of the heart. **A.** In lead I, the impulse is moving toward the positive electrode and is recorded as a positive deflection. **B.** In lead II, the impulse is moving perpendicular to the lead axis, and an equiphasic or straight line is recorded. **C.** In lead III, the impulse is moving toward the negative electrode and is recorded as a negative deflection.

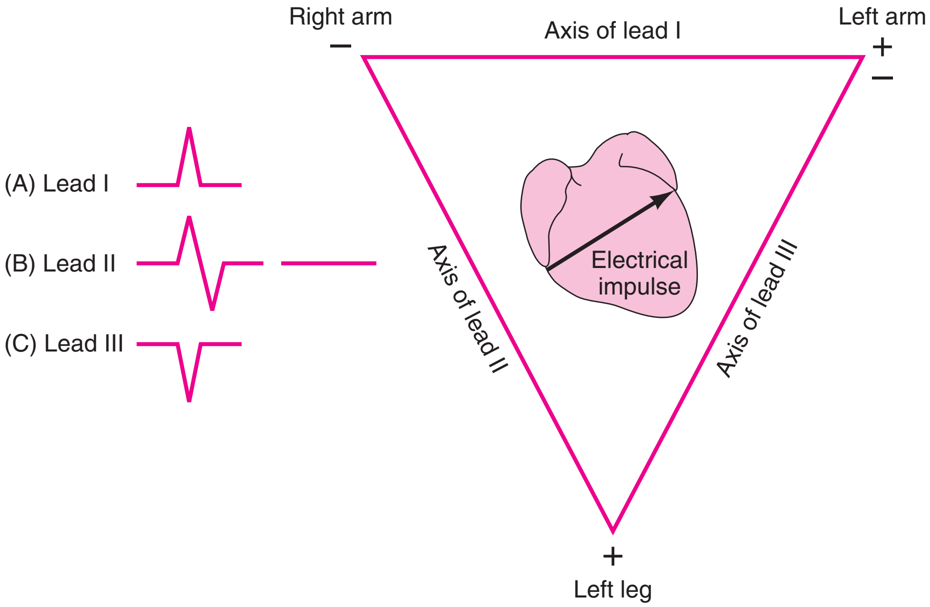

Right arm
−
Axis of lead I
Left arm
+
−
(A) Lead I
(B) Lead II
(C) Lead III
Electrical impulse
Axis of lead II
Axis of lead III
+
Left leg

FIGURE 13-4 In the normal heart, the dominant electrical current in the heart flows from the base to the apex in a right-to-left direction.

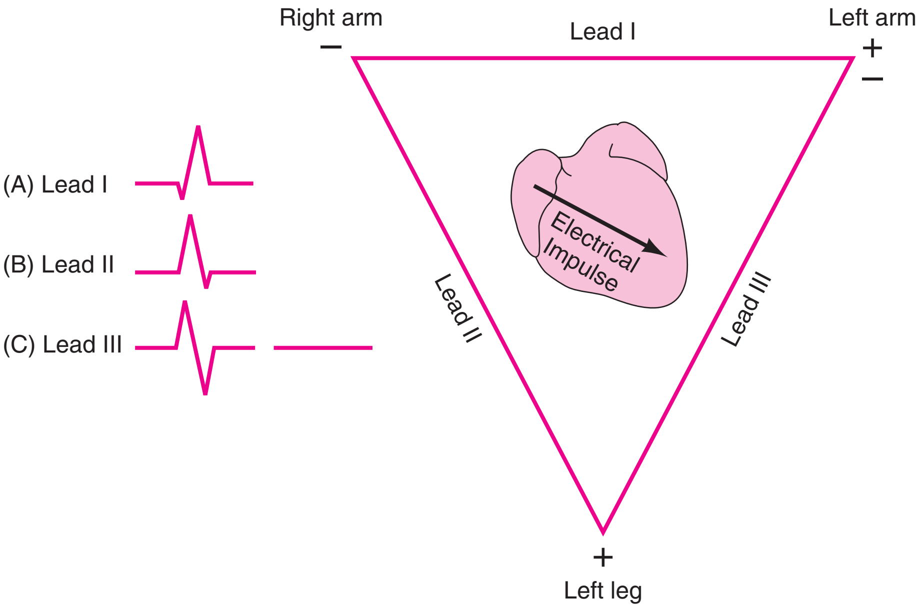

Right arm
−
Lead I
Left arm
+
−
(A) Lead I
(B) Lead II
(C) Lead III
Electrical Impulse
Lead II
Lead III
+
Left leg

FIGURE 13-5 The frontal plane and the limb leads.

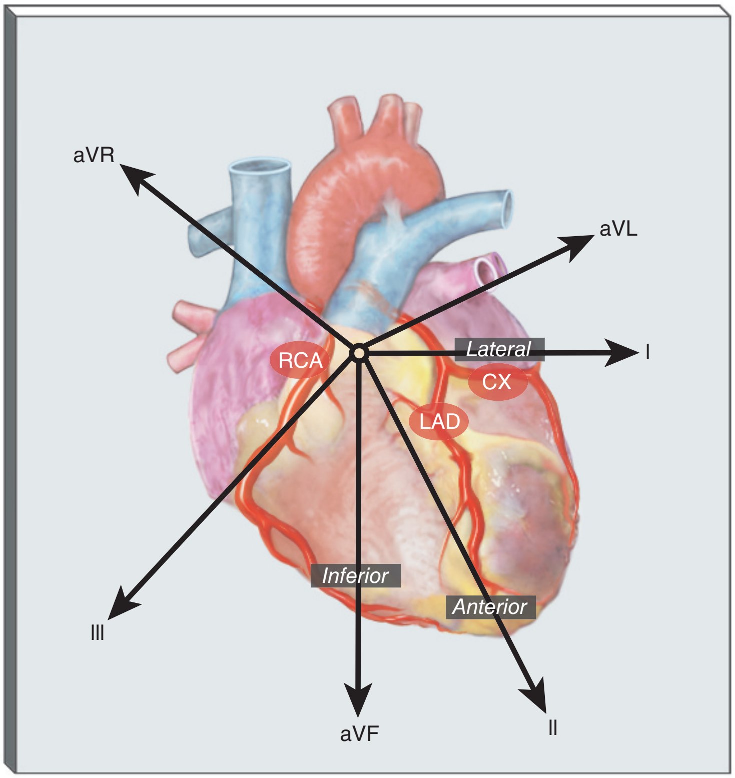

aVR
aVL
RCA
Lateral
I
CX
LAD
Inferior
Anterior
III
aVF
II

FIGURE 13-6 **A.** The position of the electrodes on the rib thorax. **B.** The precordial leads as they reflect the surface of the myocardium.

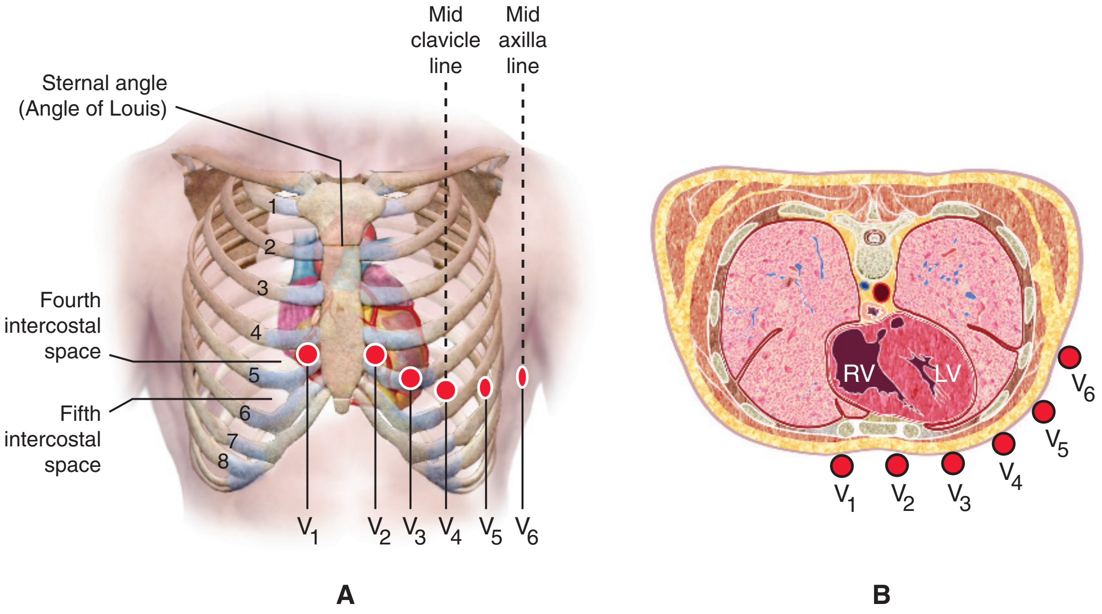

Mid clavicle line
Mid axilla line
Sternal angle (Angle of Louis)
1
2
3
4
5
6
7
8
Fourth intercostal space
Fifth intercostal space
V_1
V_2
V_3
V_4
V_5
V_6
A
RV
LV
V_1
V_2
V_3
V_4
V_5
V_6
B

FIGURE 13-7 The axes of the six precordial leads.

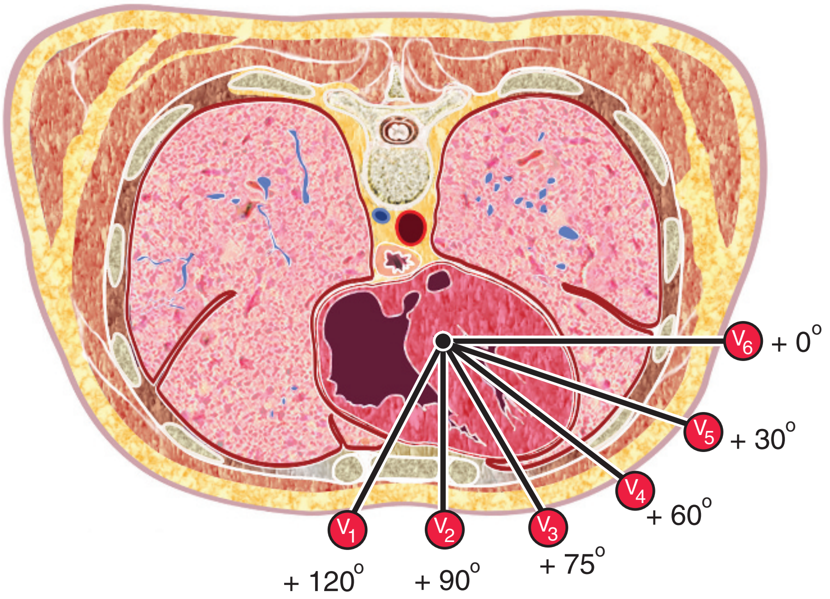

V_6 + 0°
V_5 + 30°
V_4 + 60°
V_3 + 75°
V_2 + 90°
V_1 + 120°

FIGURE 13-8 The horizontal plane and its leads.

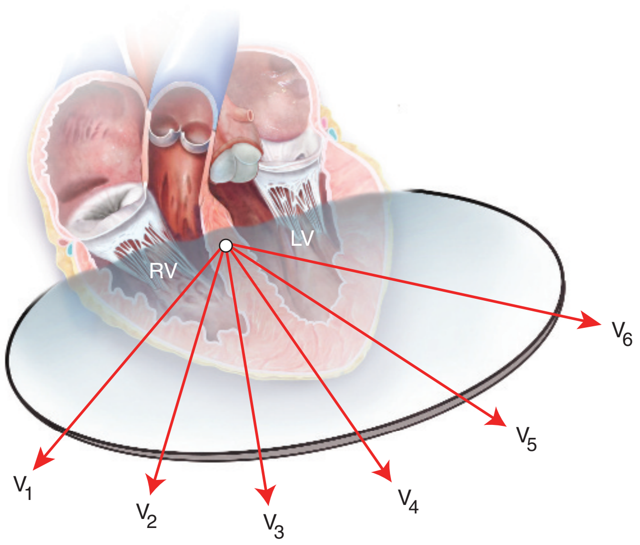
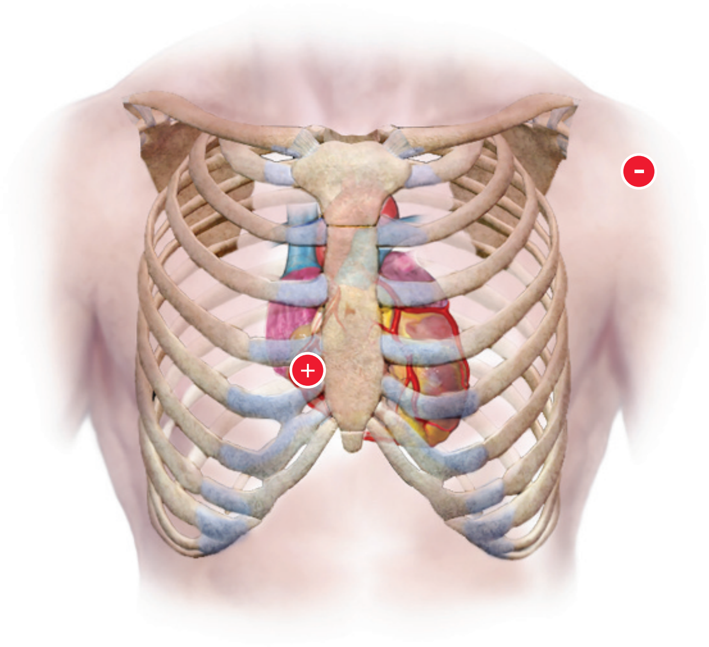

LV
RV
V_6
V_5
V_1
V_2
V_3
V_4

FIGURE 13-9 The position of the electrodes for the monitoring system MCL_1.



Normal ECG Configurations and Their Expected Measurements (Lead II)

The ECG Paper

All ECG systems use the same standard paper and run at the same speed of 25 mm/sec (Figure 13–10). From left to right, each **small square** has a duration of 0.04 second. Each **large square**, delineated by the darker lines, has five small squares, and a duration of 0.20 second. The paper on all ECG monitors runs at a speed of 5 large squares per second, or 300 large squares per minute (5 large squares × 60 seconds = 300 squares/min). The vertical portion of each small square also represents an **amplitude** (or voltage) of **0.1 millivolt** (mV), and **1 millimeter** (1 mm) in distance. Prior to each test, the ECG monitor is standardized so that 1 mV is equal to 10 mm (10 small vertical squares). As shown in Figure 13–11, most ECG paper has small vertical line marks in the margins of every 15 large squares, or every 3 seconds (0.20 × 15 = 3 seconds). Fundamental to the evaluation and interpretation of ECG recordings is the ability to measure the duration and amplitude of the waveforms.

The electrical activity of the heart is monitored and recorded on the ECG paper. As illustrated in Figure 13–12, the normal ECG configurations are composed of **waves**, **complexes**, **segments**, and **intervals** recorded as voltage (on a vertical axis) against time (on a horizontal axis). A single *waveform* begins and ends at the baseline. When the waveform continues past the baseline, it changes into another waveform. Two or more waveforms together are a *complex*. A flat, straight, or isoelectric line is called a *segment*. A waveform, or complex, connected to a segment is called an *interval*. All ECG tracings above the baseline are described as **positive** deflections. Waveforms below the baseline are **negative** deflections.

FIGURE 13-10 The ECG monitoring paper, with the blocks enlarged to illustrate the minimum units of measurement. The smallest of the blocks has three values (see solid red block): 0.04 second in duration (horizontal measurement), 0.1 mV in amplitude (vertical measurement), and 1 mm in height (also a vertical measurement). Five horizontal blocks would measure 0.20 second. Five blocks on the vertical would measure 5 mm and/or 0.5 mV. Note the darker lines that delineate five of the smallest blocks.

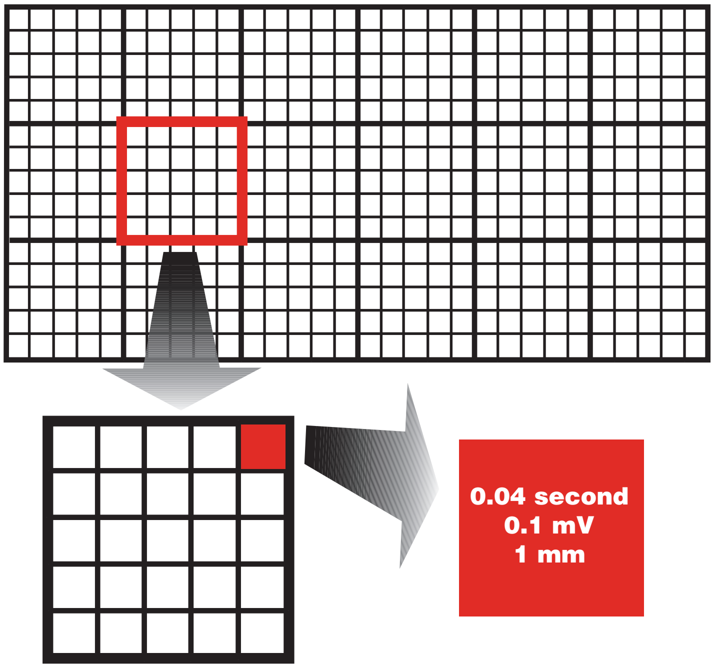


FIGURE 13–11 ECG monitoring paper showing markers indicating 3- and 6-second intervals. There are 15 blocks in 3 seconds and 30 blocks in 6 seconds.

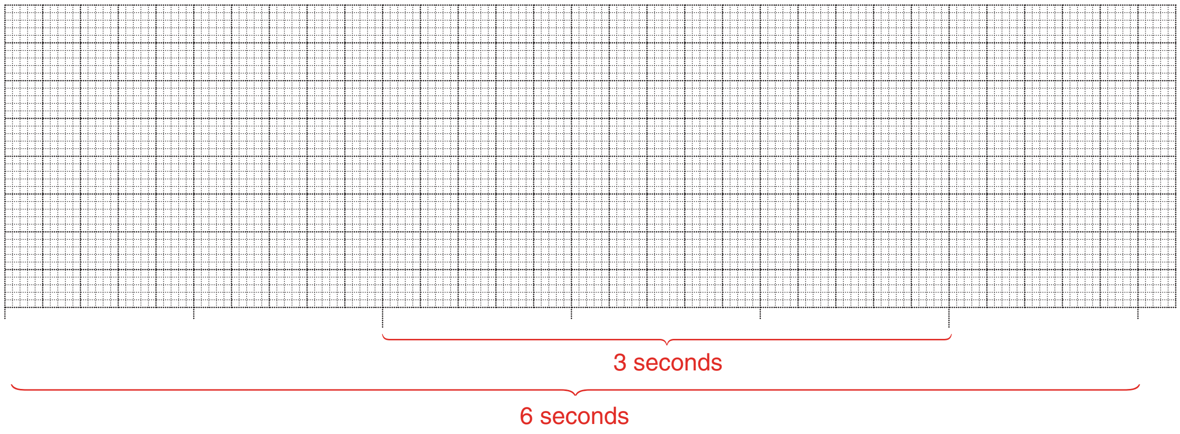
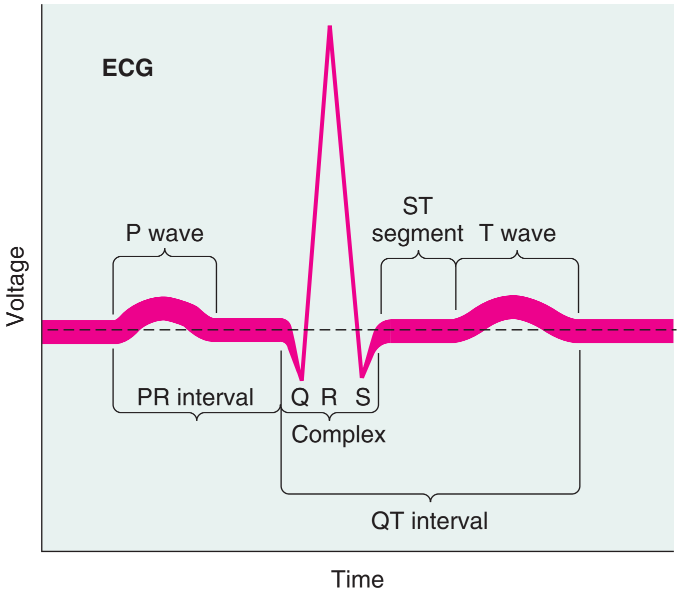


FIGURE 13–12 The normal ECG configurations.

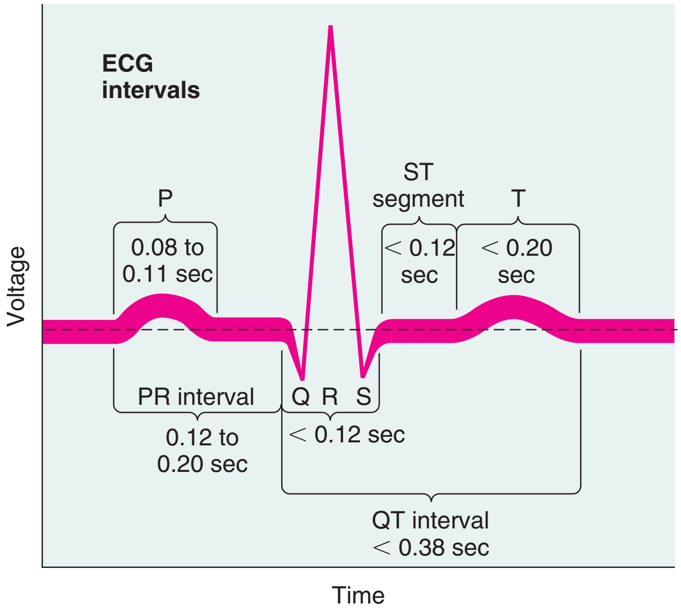


The P Wave

The normal cycle of electrical activity in the heart begins with atrial depolarization and is recorded as the *P wave.* The shape of the P wave is usually symmetrical and upright. The P wave is followed by a short pause, while the electrical current passes through the AV node. This is seen on the ECG tracing as a flat, or isoelectric, line (a segment) after the P wave. The normal duration of the P wave is 0.08 to 0.11 second (2 to $2\frac{1}{2}$ small horizontal squares). The normal amplitude of the P wave is 0.2 and 0.3 mV (2 to 3 small vertical squares) (Figure 13–13).

An increased duration or amplitude of the P wave indicates the presence of atrial abnormalities, such as hypertension, valvular disease, or congenital heart defect. Repolarization of the atria is usually not recorded on an ECG tracing, because atrial repolarization normally occurs when the ventricles are

FIGURE 13–13 The durations of the normal ECG configurations.



depolarizing, which is a greater electrical activity. When depolarization of the atria occurs from outside the SA node, the P wave configuration appears different than an SA node-induced P wave. The rhythm of the SA wave will also be disrupted and reset. When the atria depolarize in response to a stimulus outside the SA node, the wave is called a *P prime (P′) wave*.

The PR Interval

The *PR interval* starts at the beginning of the P wave and ends at the beginning of the QRS complex. The normal duration of the PR interval is 0.12 to 0.20 second (3 to 5 small horizontal squares). The PR interval represents the total atrial (supraventricular) electrical activity prior to the activation of the bundle of His, ventricular branches, and Purkinje fiber system (see Figure 13–13).

The QRS Complex

The *QRS complex* represents ventricular depolarization. Because the muscle mass of the ventricles is greater than that of the atria, the amplitude of the QRS complex is higher than the P wave. The QRS complex consists of three separate waveforms: **Q wave**, **R wave**, and **S wave**. The first negative defection (below the baseline) after the P wave is the *Q wave* (Figure 13–14A). The next tall positive deflection (above the baseline) is the *R wave* (Figure 13–14B). The S *wave* is the small negative deflection (below the baseline) that follows the R wave (Figure 13–14C).

FIGURE 13–14 **A.** Q waveform of the QRS complex. **B.** R waveform of the QRS complex. **C.** S waveform of the QRS complex.

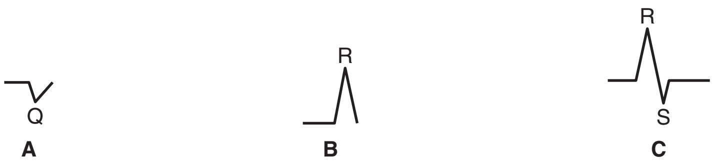
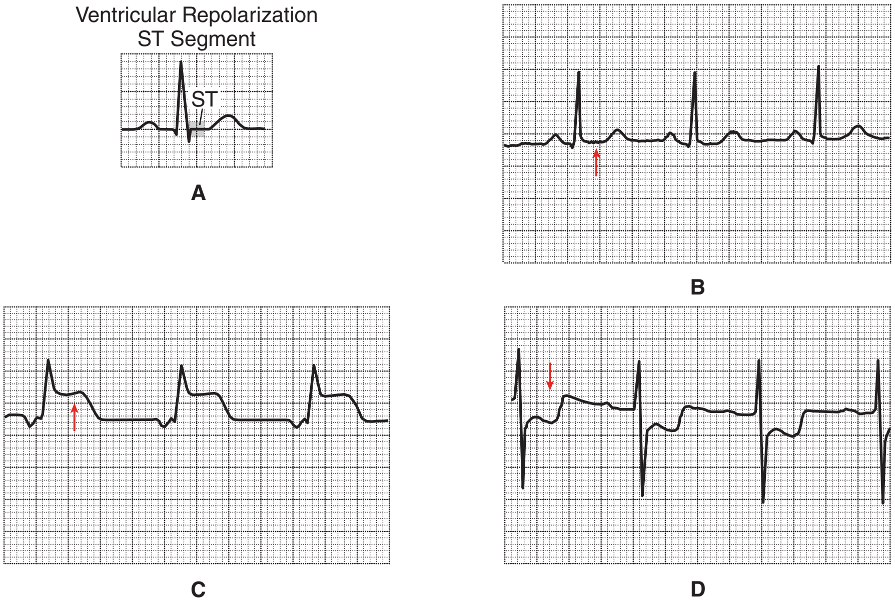


FIGURE 13-15 **A.** The ST segment highlighted within cardiac complex. **B.** Note the variations in ST segments at the baseline. **C.** 3-mm ST segment ↑. **D.** 3-mm ST segment ↓.



Relative to the ECG lead, the QRS complex may not have a Q wave or an S wave. Under normal conditions, the duration of the QRS complex is less than 0.12 second ($2\frac{1}{2}$ little squares) (see Figure 13–13). Abnormal ventricular-induced QRS complex waves are longer than 0.12 second. Other characteristics of an abnormal QRS complex include premature ventricular contractions (PVCs), increased amplitude, and T waves of opposite polarity.

The ST Segment

The *ST segment* represents the time between ventricular depolarization and repolarization (see Figure 13–13). The ST segment begins at the end of the QRS complex (called the J point) and ends at the beginning of the T wave. Normally, the ST segment measures 0.12 second or less. The ST segment may be elevated or depressed due to myocardial injury, ischemia, and certain cardiac medications. A flat, horizontal ST segment above or below the baseline is highly suggestive of ischemia. Figure 13–15 shows four different ST segment variations.

The T Wave

The *T wave* represents ventricular repolarization, rest, and recovery (see Figure 13–13). Normally, the T wave has a positive deflection of about 0.5 mV, although it may have a negative deflection. It may, however, be of such low amplitude that it is difficult to read. The duration of the T wave normally measures 0.20 second or less.

At the beginning of the T wave, the ventricles are in their effective refractory period. At about the peak of the T wave, the ventricles are in their relative refractory period and, thus, are vulnerable to stimulation (see Figure 13–13). T waves are sensitive indicators for the presence of a number of abnormalities, including acid–base imbalances, hyperventilation, hyperkalemia, ischemia, and the use of various drugs. Figure 13–16 shows common T wave variations.

FIGURE 13-16 **A.** The T wave representing ventricular depolarization. **B.** Measuring the T wave with ST segment elevation. **C.** Measuring an inverted T wave with ST segment depression.

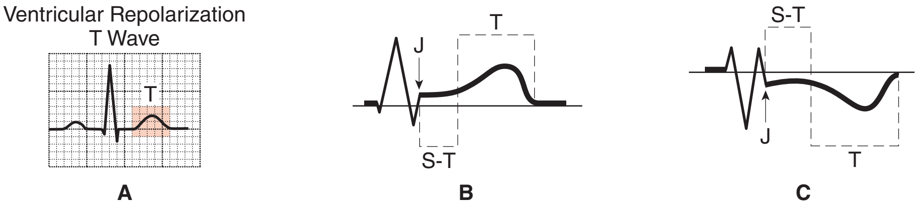
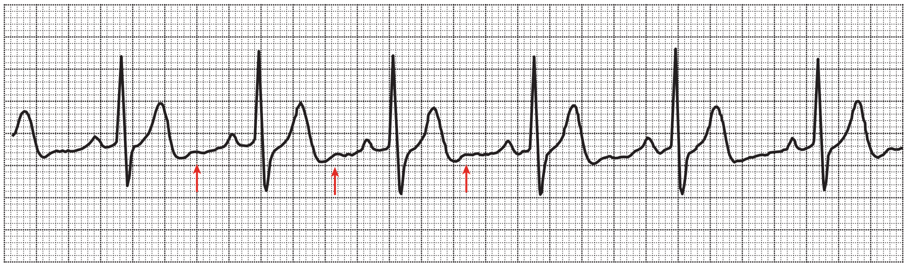


FIGURE 13-17 The U wave highlighted (arrow) within the cardiac complex. U waves plot only with other U waves, just as P waves plot with P waves, and QRS plots with the QRS complex.



The U Wave

The *U wave* follows the T wave and has the same polarity (deflection) as the T wave (Figure 13–17). Its origin and mechanism are not known. Because of its low voltage, the U wave usually is flat and not seen; however, it often becomes prominent in the presence of certain electrolyte disturbances, certain medications, and heart disease.

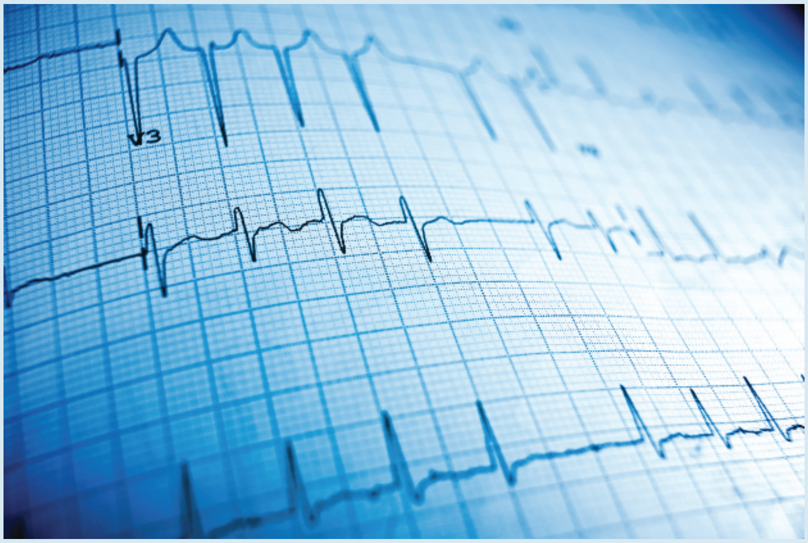
The QT Interval

The *QT interval* is measured from the beginning of the QRS complex to the end of the T wave (see Figure 13–13). The QT interval represents total ventricular activity—that is, ventricular depolarization (QRS) and repolarization (ST segment and the T wave). The normal QT interval measures about 0.38 second and varies in males and females and with age. As a general rule, the QT interval should be about 40 percent of the measured RR interval.

Finally, note that the QT interval varies indirectly to the heart rate; that is, the faster the heart rate, the shorter the QT interval time. This is because when the heart rate is fast, repolarization is also faster. The QT interval time is longer with slower heart rates. The QT interval often varies with use of certain cardiac drugs that alter the heart's action potential and refractory times.

Clinical Connection 13-1

Electrocardiograms (ECGs)—The Role of the Respiratory Therapist



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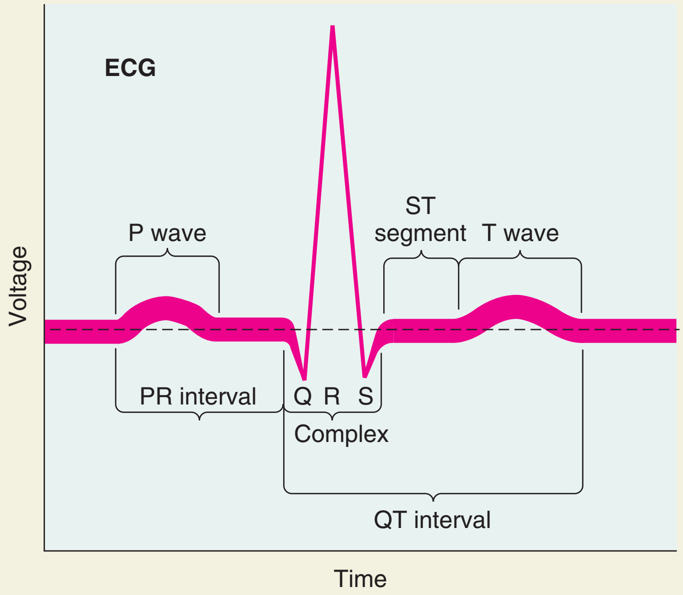
In many hospitals throughout the United States, the respiratory therapist is the person who obtains the ECG—which places the respiratory therapist at the patient's bedside at a prime time to both witness and respond to life-threatening dysrhythmias. This is why the respiratory practitioner must have a good ECG knowledge base; the therapist must also be able to interpret ECG results correctly. Without a doubt, the early recognition—and intervention—of a serious cardiac problem can minimize heart damage. Oftentimes, the respiratory therapist serves as the first link in care for the patient experiencing a cardiac arrest and is a vital part of the health care team once the patient has stabilized. In addition, a fundamental knowledge base and understanding of ECG changes can further enhance the respiratory therapist's patient assessment and treatment plans. Chapter 14 provides the reader the essential information required to interpret the most commonly seen cardiac dysrhythmias.

Chapter Summary

The electrocardiogram (ECG) is a graphic representation of the electrical activity of the heart's conductive system monitored and recorded over a period of time. The essential knowledge components for the standard 12-ECG system include (1) the standard limb leads—leads I, II, III, aVR, aVL, and aVF; (2) how an electrical impulse of the ventricle is recorded; (3) the precordial (chest) leads—V_1, V_2, V_3, V_4, V_5, and V_6; and (4) the normal ECG configurations. Table 13–2 summarizes the normal ECG configurations and corresponding activity of the heart. The clinical connection associated with these topics includes the electrocardiogram—the role of the respiratory therapist.

TABLE 13-2 Summary of Normal ECG Configurations and Heart Activity



ECG Configuration	Heart Activity
P wave	Atrial depolarization
PR interval	Total atrial electrical activity prior to activation of the bundle of His, ventricular branches, and Purkinje fiber system
QRS complex	Ventricular depolarization
ST segment	Time between ventricular depolarization and repolarization
T wave	Ventricular repolarization
U wave	Usually is flat or not seen. Often prominent in the presence of certain electrolyte disturbances, certain medications, and heart disease
QT interval	Total ventricular activity (QRS complex, ST segment, and T wave)

Review Questions

1. Which of the following is (are) unipolar leads?

1. aVL
2. Lead II
3. V6
4. Lead III
5. aVR

A. 3 only
B. 1 and 5 only
C. 2 and 4 only
D. 1, 3, and 5 only

2. The imaginary line that can be drawn between the positive and negative electrodes in leads I, II, and III is called the

A. Axis
B. Vector
C. Equiphasic line
D. Baseline

3. Which of the following monitor the electrical activity of the heart in the frontal plane?

1. aVL
2. Lead II
3. aVR
4. Lead III
5. aVF
    A. 1 and 3 only
    B. 1, 4, and 5 only
    C. 2, 3, 4, and 5 only
    D. 1, 2, 3, 4, and 5

4. Which of the following monitor(s) the left ventricle?

1. V1
2. V2
3. V3
4. V5
5. V6
    A. 1 only
    B. 5 only
    C. 2 and 3 only
    D. 4 and 5 only

5. The small squares on the standard ECG paper represent

A. 0.02 second
B. 0.04 second
C. 0.06 second
D. 0.08 second

6. The normal duration of the P wave is no longer than

A. 0.80 second
B. 0.11 second
C. 0.15 second
D. 0.20 second

7. The normal duration of the PR interval is no longer than

A. 0.12 second
B. 0.15 second
C. 0.20 second
D. 0.50 second

8. The normal duration of the QRS complex is less than

A. 0.01 second
B. 0.05 second
C. 0.12 second
D. 0.15 second

9. The normal duration of the ST segment is

A. 0.12 second or less
B. 0.15 second or less
C. 0.20 second or less
D. 0.50 second or less

10. The normal duration of the T wave is

A. 0.05 second or less
B. 0.10 second or less
C. 0.15 second or less
D. 0.20 second or less

83
P2-4AC
15.0 cm MI 0.9
Gen Tls 1.1
[2d] G78/71 d
FA4/P90
HAR/FSI0
[C] G50/0.80 kHz
FA5/F1/8
TDI
Amplitude (V)
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
-0.2
T
U
S-T
interval
2.5
3
Time (s)
3.5

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CHAPTER 14

ECG Interpretation

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the systematic approach to ECG interpretation.
2. Explain the P wave, PR interval, QRS complex, QRS rate, and QRS rhythm in the normal sinus rhythm.
3. Describe the P wave, PR interval, QRS complex, QRS rate, and QRS rhythm in abnormal sinus mechanisms.
4. Describe the P wave, PR interval, QRS complex, QRS rate, and QRS rhythm in abnormal atrial mechanisms.
5. Describe the P wave, PR interval, QRS complex, QRS rate, and QRS rhythm for abnormal ventricular mechanisms.
6. Describe the P wave, PR interval, QRS complex, QRS rate, and QRS rhythm in atrioventricular (AV) defects.

How to Analyze the Waveforms[1]

There are many correct ways in which to approach electrocardiogram (ECG) interpretation. Fundamental to all good methods is a consistent, systematic approach. Some practitioners, for example, begin by looking at the P waves and then move on to the QRS complexes, whereas others start by looking at the QRS complexes and then the P waves. Both approaches are correct. The key is to be systematic and consistent. Table 14–1 provides an overview of the steps involved in a good systematic approach to ECG analysis. A short discussion of this approach follows.

Step 1: Does the General Appearance of the ECG Tracing Appear Normal or Abnormal?

Closely scan the ECG tracing and identify each of the wave components. Note any specific wave abnormalities. Are there any abnormalities—in terms of appearance or duration—in the P waves, QRS complexes, ST segments, or T waves? Do the complexes appear consistent from one beat to the next? Does the rate appear too slow or too fast? Does the rhythm appear regular or irregular? Are there any extra beats or pauses? It is often helpful to circle any possible abnormalities during step 1. This initial process helps to pinpoint problem areas that can be inspected more carefully during the steps discussed next.

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[1] For the definition of P wave, PR interval, QRS complex, ST segment, T wave, U wave, and QT interval, see Chapter 13.

TABLE 14-1 Systematic Approach to ECG Interpretation

Step 1:	General inspection
Step 2:	Analysis of ventricular activity (QRS complexes) • Rate • Rhythm • Shape
Step 3:	Analysis of atrial activity • Rate • Rhythm • Shape
Step 4:	Assessment of atrioventricular relationship • Conduction ratio • Discharge sequence (P:QRS or QRS:P) • PR interval
Step 5:	ECG interpretation • Normal sinus rhythm • Cardiac dysrhythmias

Step 2: Does the Ventricular Activity (QRS Complexes) Appear Normal or Abnormal?

Rate

When the ventricular heart rate is **regular**, the rate can be determined by counting the number of large squares between two consecutive QRS complexes and then dividing 300 by the number of large squares. For example, if there are three large squares between two QRS complexes, then the ventricular rate would be 100 per min ($300 \div 43 = 100$) (Figure 14–1). Table 14–2 shows the estimated heart rate for different

FIGURE 14-1 ECG recording with markers denoting the number of large squares (blocks) between the QRS complexes (RR interval). Because there are three such blocks between QRS complexes, dividing 3 into 300 provides the estimated rate of 100 per minute.

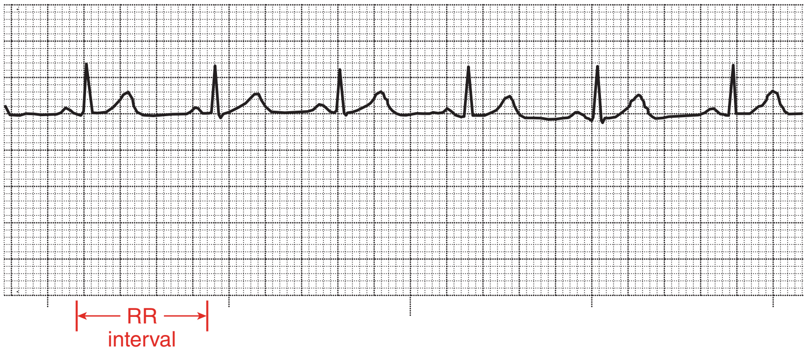


TABLE 14–2 Calculating Heart Rate by Counting the Number of Large ECG Squares

Distance between Two QRS Complexes (number of large squares)	Estimated Heart Rate (per min)
1	300
2	150
3	100
4	75
5	60
6	50

numbers of large squares between two QRS complexes. Appendix VII provides a more complete presentation of the estimated heart rate for different numbers of large squares between two QRS complexes.

When the ventricular heart rate is **irregular**, the rate can be calculated by using the vertical 3-second marks in the upper margins of the ECG paper. This is done by counting the number of QRS complexes in a 6-second interval (two 3-second marks), then multiplying this number by 10. For example, if seven QRS complexes are present in two 3-second intervals (6 seconds), then the ventricular rate is about 70 beats/min (bpm) (7 × 10 = 70). Normal *adult* heart rate is between 60 and 100 bpm. A heart rate of less than 60 bpm is classified as **bradycardia**. A heart rate greater than 100 bpm is called **tachycardia**.

Rhythm

The ventricular rhythm is determined by comparing the shortest RR intervals with the longest RR intervals. When the time variation between the shortest RR interval and the longest RR interval is greater than 0.12 second, the rhythm is *irregular;* a variation of 0.12 or less is a *regular* rhythm.

Shape

Finally, determine if the shape of the QRS complexes is identical from one complex to another. Is the polarity of the QRS complexes appropriate for the specific monitoring leads? The shape as well as the duration of the QRS complex help to determine the origin of the ventricular depolarization. The normal QRS duration is 0.10 second (2.5 little squares) or less. A QRS complex that is narrow and lasts 0.10 second or less represents a **supraventricular origin** (i.e., sinoatrial [SA] node or atrial source) and normal intraventricular conduction. When the QRS complex is greater than 0.10 second and the shape is distorted (e.g., increased amplitude, opposite polarity, slurred), then an abnormal electrical source (ectopic focus) is likely to be present within the ventricle.

Step 3: Does the Atrial Activity Appear Normal or Abnormal?

Similar to the assessment of the QRS complexes, the rate, rhythm, and shape of the atrial activity (P waves) are evaluated. The **rate** of the atrial activity is calculated in the same way as the QRS complexes (see Table 14–2). Normally, the P wave rate and the QRS rate are the same. The atrial **rhythm** is calculated in the same way as the QRS rhythm, except that in this case PP intervals are used. The shape of the P waves is then evaluated. Abnormalities may include P waves that are not of expected polarity, atrial flutter, fibrillation, or P prime (P′) waves (i.e., waves initiated outside the SA node).

Step 4: Does the Atrioventricular (AV) Relationship Appear to be Normal?

Is the AV conduction ratio 1:1? In other words, is a P wave followed by a QRS complex? When the AV conduction ratio is greater than 1:1 (e.g., 2:1, 3:1), not all the atrial impulses are being conducted to the ventricles. For example, an AV conduction ratio of 2:1 or 3:1 indicates that every second or third atrial impulse is being blocked. In some cases, the AV conduction is completely blocked and the P waves and QRS complexes are totally unrelated. The best method to determine the AV conduction ratio is to ask these two questions:

1. Is each P wave followed by a QRS complex?
2. Is each QRS complex preceded by a single P wave?

When the answer to each of these questions is no, evaluate the rhythm to determine if a pattern exists. An excellent method to determine this is to measure the PR intervals to see if the intervals are fixed or variable. The PR interval is measured from the beginning of the P wave to the start of the QRS complex. The PR interval represents the time between the start of atrial depolarization to the beginning of ventricular depolarization. During a normal sinus rhythm, the PR interval is constant from one beat to the next and is no longer than 0.20 second. A PR interval greater than 0.20 second represents an abnormal delay in AV conduction.

Step 5: What Is the ECG Interpretation?

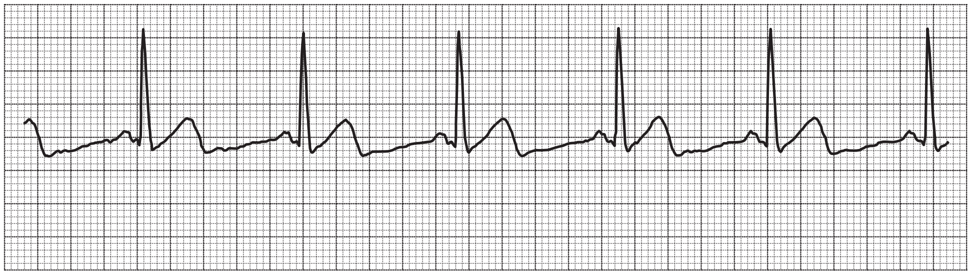
Normal Sinus Rhythm

If there are no variations from the normal sinus rhythm (NSR)—the gold standard by which most ECG dysrhythmias are measured, compared, and analyzed—then the ECG tracing is normal. When the ECG tracing varies from the normal sinus rhythm, however, the interpretation must incorporate all the information that describes the abnormal electrical activity of the heart. Thus, in view of these facts, the recognition of the normal sinus rhythm is an essential prerequisite to the interpretation of abnormal ECG tracings. The following summarizes the ECG characteristics of the normal sinus rhythm, as viewed from lead II:

- **P wave:** The P waves are positive (upright) and uniform. A QRS complex follows every P wave.
- **PR interval:** The duration of the PR interval is between 0.12 and 0.20 second and is constant from beat to beat.
- **QRS complex:** The duration of the QRS complex is 0.12 second or less. A P wave precedes every QRS complex.
- **QRS rate:** Between 60 and 100 bpm.
- **QRS rhythm:** Regular.

Figure 14–2 shows an ECG tracing of a normal sinus rhythm.

FIGURE 14-2 ECG tracing of a normal sinus rhythm.



Common Cardiac Dysrhythmias

The most common cardiac dysrhythmias can be subdivided into the following four major categories: sinus mechanisms, atrial mechanisms, ventricular mechanisms, and AV conduction defects. Table 14–3 provides an overview of the major dysrhythmias found under each of these categories.

The Sinus Mechanisms

Sinus Bradycardia

Bradycardia means "slow heart." In *sinus bradycardia,* the heart rate is less than 60 bpm. The ECG characteristics of sinus bradycardia in lead II are as follows:

- **P wave:** The P waves are positive and uniform. Each P wave is followed by a QRS complex.
- **PR interval:** The PR interval has a normal duration between 0.12 and 0.20 second and is constant from beat to beat.
- **QRS complex:** The QRS complex duration is 0.12 second or less. A P wave precedes every QRS complex.
- **QRS rate:** Less than 60 bpm.
- **QRS rhythm:** Regular.

Figure 14–3 shows an ECG tracing of sinus bradycardia. Figure 14–4 shows the presence of sinus bradycardia in two leads in a healthy adult.

TABLE 14-3 Common Cardiac Dysrhythmias

Sinus Mechanisms	Atrial Mechanisms	Ventricular Mechanisms	AV Conduction Defects
Sinus bradycardia Sinus tachycardia Sinus arrhythmia Sinus block Sinus arrest	Premature atrial complex (PAC) Atrial bigeminy Atrial tachycardia Atrial flutter Atrial fibrillation	Premature ventricular complex (PVC) Uniform PVCs Multiform PVCs Paired PVCs Bigeminal PVCs Trigeminal PVCs Ventricular tachycardia Ventricular flutter Ventricular fibrillation Asystole	Sinus rhythm with first-degree AV block Sinus rhythm with second-degree AV block Complete AV block

FIGURE 14-3 An ECG tracing showing one (+) P wave to the left of each QRS complex; the PR interval is consistent, and the heart rate is less than 60 bpm. These computations represent a sinus bradycardia.

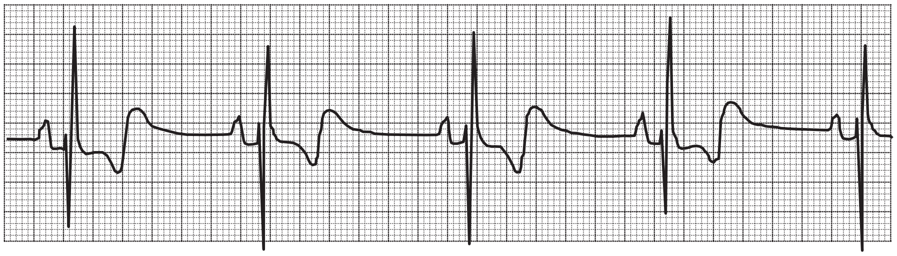
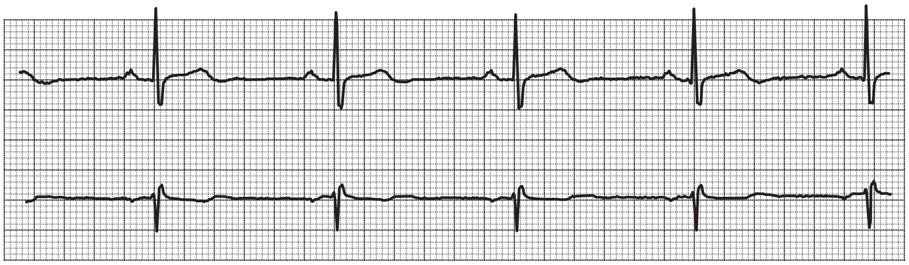


FIGURE 14-4 An ECG tracing showing sinus bradycardia in two leads from a physically fit adult.



Sinus bradycardia is often normal in athletes who have increased their cardiac stroke volume through physical conditioning. Common pathologic causes of sinus bradycardia include a weakened or damaged SA node, severe or chronic hypoxemia, increased intracranial pressure, obstructive sleep apnea, and use of certain drugs (most notably beta-blocking agents). Sinus bradycardia may lead to a decreased cardiac output and lowered blood pressure. In severe cases, sinus bradycardia may lead to a decreased perfusion and tissue hypoxia. The individual may have a weak or absent pulse, poor capillary refill, cold and clammy skin, and a depressed sensorium.

Sinus Tachycardia

Tachycardia means "fast heart." In *sinus tachycardia,* the heart rate is between 100 and 160 bpm, and the rhythm is regular. The ECG characteristics of sinus tachycardia in lead II are as follows:

- **P wave:** The P waves are positive and uniform. Each P wave is followed by a QRS complex.
- **PR interval:** The PR interval has a normal duration between 0.12 and 0.20 second and is constant from beat to beat.
- **QRS complex:** The QRS complex duration is 0.12 second or less. A P wave precedes every QRS complex.
- **QRS rate:** Between 100 and 160 bpm.
- **QRS rhythm:** Regular.

Clinical Connection 14-1

Bradycardia: ACLS* Treatment Protocol

As presented earlier, bradycardia is defined as any rhythm with a heart rate less than 60 beats per minute in an adult. Note, however, that ACLS standards further differentiate between bradycardia and symptomatic bradycardia as follows: **symptomatic bradycardia** is a heart rate less than 60 bpm with the presence of the following three criteria:

- The heart rate is slow.
- The patient is demonstrating symptoms.
- The symptoms are due to the slow heart rate.

Treatment

- **Atropine:** The first drug of choice for symptomatic bradycardia.
- **Dopamine:** Second-line drug for symptomatic bradycardia when atropine is not effective.
- **Epinephrine:** Can be used as an equal alternative to dopamine when atropine is not effective.

The treatment of symptomatic bradycardia also includes the assessment of contributing causes. In addition, transcutaneous pacing may be appropriate in the treatment of some patients with symptomatic bradycardia.

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*Advanced Cardiac Life Support (http://acls-algorithms.com).

FIGURE 14-5 An ECG tracing from an exercising adult. Note there is a single (+) P wave to the left of each QRS complex; the rate is 150 bpm.

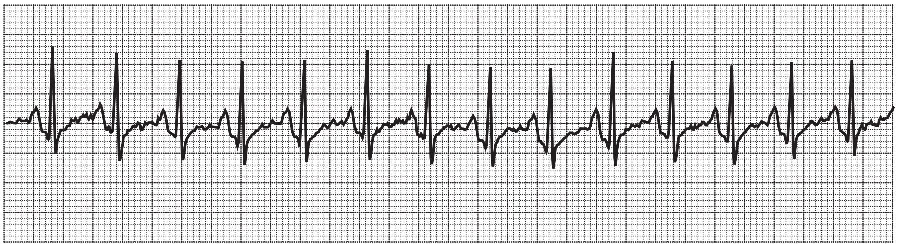


Figure 14–5 shows an ECG tracing of sinus tachycardia.

In adults, sinus tachycardia is the normal physiologic response to exercise, emotions, fever, pain, fear, anger, and anxiety. Sinus tachycardia is also caused by physiologic stress such as hypoxemia, hypovolemia, severe anemia, hyperthermia, massive hemorrhage, hyperthyroidism, and any condition that leads to an increased sympathetic stimulation. Pathologic conditions associated with sinus tachycardia include congestive heart failure, cardiogenic shock, myocardial ischemia, heart valve disorders, pulmonary embolism, hypertension, and infarction.

Sinus Dysrhythmia

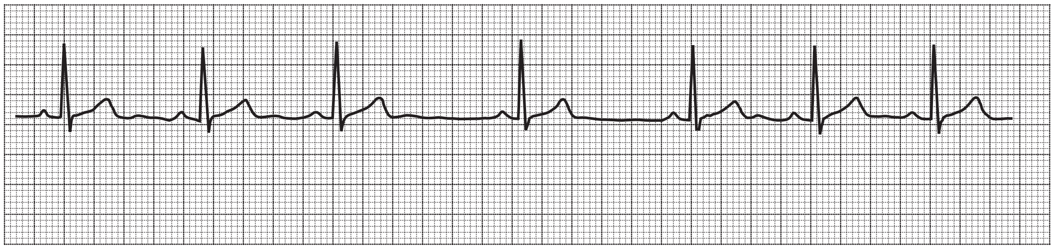
In *sinus dysrhythmia,* the heart rate varies by more than 10 percent. The P-QRS-T pattern is normal, but the interval between groups of complexes (e.g., the PP or RR intervals) varies. The ECG characteristics in sinus dysrhythmia in lead II are as follows:

- **P wave:** The P waves are positive and uniform. Each P wave is followed by a QRS complex.
- **PR interval:** The PR interval has a normal duration between 0.12 and 0.20 second and is constant from beat to beat.
- **QRS complex:** The QRS complex duration is 0.12 second or less. A P wave precedes every QRS complex.
- **QRS rate:** Varies by more than 10 percent.
- **QRS rhythm:** Irregular.

Figure 14–6 shows an ECG tracing of a sinus dysrhythmia.

A sinus dysrhythmia is normal in children and young adults. The patient's pulse will often increase during inspiration and decrease during expiration. No treatment is required unless there is a significant alteration in the patient's arterial blood pressure.

FIGURE 14-6 An ECG tracing of sinus arrhythmia 54 to 71 bpm.



Sinus (SA) Block

In a *sinus (SA) block,* also called a *sinus exit block,* the SA node initiates an impulse but the electrical current through the atria is blocked. Thus, the atria—and the ventricles—do not depolarize or contract, resulting in no P wave or QRS complex. The next P-QRS-T complex, however, appears at the precise time it would normally appear if the sinus block had not occurred. In other words, the ECG shows that the heart has skipped a beat. The ECG characteristics for sinus block in lead II are as follows:

- **P wave:** The P waves are positive and uniform; however, an entire P-QRS-T complex is missing.
- **PR interval:** The PR interval has a normal duration between 0.12 and 0.20 second and is constant from beat to beat, except for the pause when an entire cycle is missing. The PR interval may be slightly shorter after the pause.
- **QRS complex:** Except for the missing cycle, the QRS complex duration is 0.12 second or less, and a P wave precedes every QRS complex.
- **QRS rate:** The rate may vary according to the number and position of missing P-QRS-T cycles.
- **QRS rhythm:** The rhythm may be regular or irregular according to the number and position of missing P-QRS-T cycles.

Figure 14–7 shows an ECG tracing of a sinus block.

Sinus Arrest

Sinus arrest (SA node arrest) is the sudden failure of the SA node to initiate an impulse (i.e., no P wave). It is common to see two, three, or four P-QRS-T complexes missing following a normal P-QRS-T complex. This period of inactivity is then followed by a normal sinus rhythm. Generally, there is no pattern of frequency of occurrence; that is, the individual may demonstrate one or two periods of sinus arrests and then demonstrate a normal sinus rhythm for minutes, or even hours, before another sinus arrest appears. When the sinus arrest is excessively long, the AV node usually takes over and initiates a new (but slower) rhythm called an *escape rate.* The ECG characteristics for sinus arrest in lead II are as follows:

- **P wave:** No P wave.
- **PR interval:** The PR interval has a normal duration between 0.12 and 0.20 second and is constant from beat to beat.
- **QRS complex:** The QRS complex duration is 0.10 second or less. After a sinus arrest, however, the QRS duration may be greater than 0.12 second when the escape rhythm is initiated by the AV node.
- **QRS rate:** Normal sinus rhythm during nonsinus arrest periods.
- **QRS rhythm:** The QRS complexes before and after the sinus arrest are regular. The escape rate may be regular or irregular.

Figure 14–8 shows an ECG tracing of a sinus arrest.

FIGURE 14-7 An ECG tracing showing SA block.

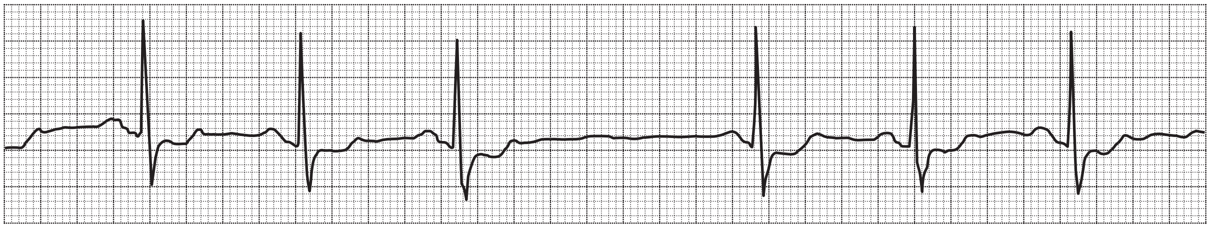
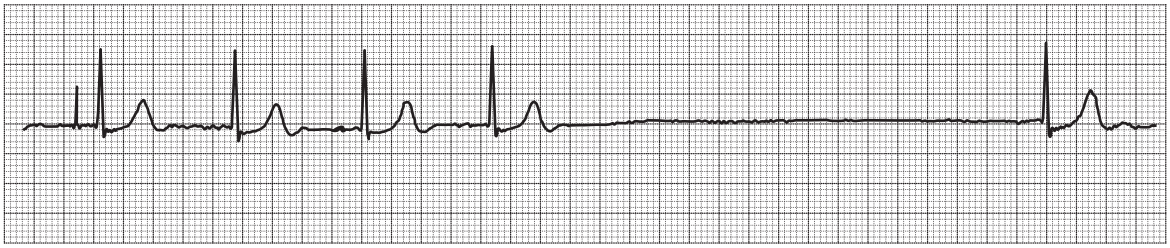


FIGURE 14-8 An ECG tracing from an 82-year-old patient showing sinus arrest. The patient required insertion of an electronic pacemaker.



The Atrial Mechanisms

Premature Atrial Complex

A *premature atrial complex (PAC)* results when abnormal electrical activity in the atria causes the atria to depolarize before the SA node fires. An electrical current that originates outside the SA node is called an **ectopic focus**. An ectopic focus in the atria results in a **P prime** (P′) on the ECG tracing. The P′ is usually easy to identify. It will be early or premature and it will usually vary in size and shape from the normal sinus P wave. PACs also disrupt the sinus rate and rhythm. When the sinus node regains control, the rate and rhythm will return to normal. The QRS configuration is usually normal. The ECG characteristics of a PAC in lead II are as follows:

- **P wave:** The P′ wave will appear different than a normal SA node-induced P wave. The P′ may be hidden, or partially hidden, in the preceding T wave. P′ waves hidden in the T wave often distort or increase the amplitude of the T wave. A PAC may not successfully move into the ventricles if the AV node or bundle branches are in their complete refractory period. This is called a *blocked* or *nonconducted* PAC.
- **PR interval:** The P′R interval may be normal or prolonged, depending on the timing of the PAC. Most often, however, the P′R interval is different from the normal SA node rhythm.
- **QRS complex:** Except for the abnormal cycle generated by the P′ wave, the QRS complex duration is 0.12 second or less, and a normal P wave precedes every QRS complex.
- **QRS rate:** Varies.
- **QRS rhythm:** Irregular.

Figure 14–9 shows an ECG tracing of a sinus rhythm with PAC. Figure 14–10 is an ECG tracing illustrating a sinus rhythm with two nonconducted PACs.

FIGURE 14-9 An ECG tracing showing one (+) P wave to the left of each of the first three sinus beats, a sinus rhythm at 96 bpm. The next QRS complex is similar to the sinus QRS complexes but is premature and has a (+) P′ superimposed on the previous T wave. The sinus P waves do not plot through the event. The PACs recur (arrow) each time, disturbing sinus rhythm. The ECG interpretation would be sinus rhythm at 96 bpm with frequent PACs.

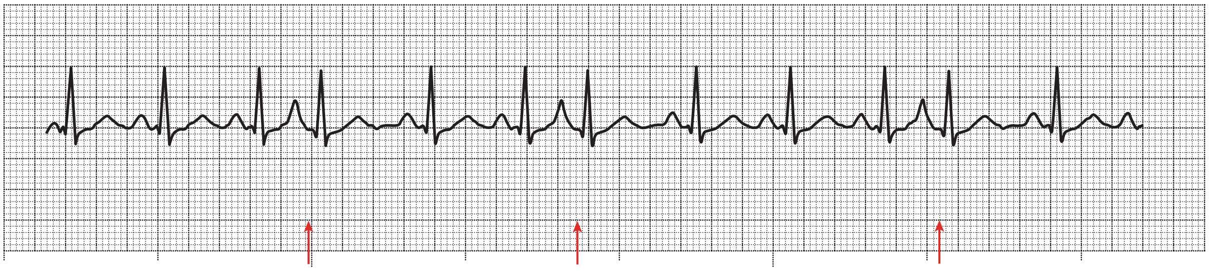
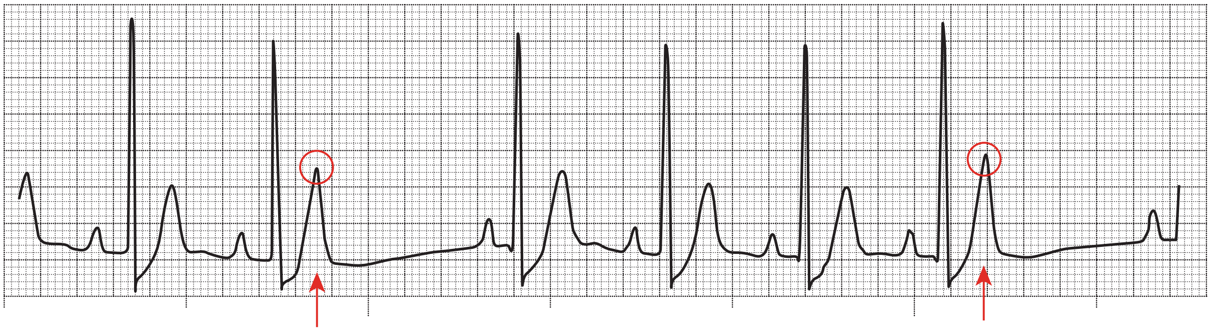


FIGURE 14-10 An ECG tracing showing one (+) P wave to the left of each of the first two sinus beats, a sinus rhythm. A sudden pause occurs in the cadence of the sinus mechanism. Look back at the last T wave and note the increased amplitude. The height of the T wave is a combination of P wave and T wave amplitudes. The sinus P waves do not plot through the event, and the cadence of the sinus rhythm resumes at about 75 bpm. The ECG interpretation would be sinus rhythm at 75 bpm with frequent, nonconducted PACs.

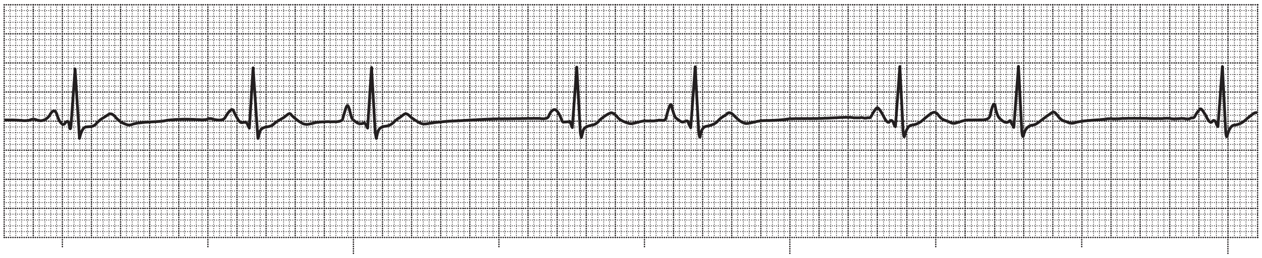


Depending on their severity and frequency, PACs may be of no clinical significance, or they may result in harmful atrial dysrhythmias. Causes of PACs include hypoxemia, impending heart failure, right coronary artery disease, excessive use of digitalis, pericarditis, ingestion of stimulants or caffeine, and recreational drug abuse. PACs are commonly seen in patients with chronic obstructive pulmonary disease (COPD) when the disease is accompanied by increased pulmonary vascular resistance. PACs are also frequently seen in females during the third trimester of pregnancy because of the increased workload of the mother's heart, which develops primarily because (1) the mother's blood volume increases by as much as 50 percent during the third trimester and (2) the additional perfusion of the fetus and placenta causes the peripheral vascular resistance to increase.

Atrial Bigeminy

Atrial bigeminy is said to be present when every other beat is an ectopic atrial beat—a PAC. In other words, the ECG tracing shows a PAC, a normal sinus beat, a PAC, a normal sinus beat, and so on (Figure 14–11). Atrial bigeminy is often one of the first signs of congestive heart failure. Patients with atrial bigeminy should be assessed for peripheral edema, sudden weight gain, and adventitious breath sounds.

FIGURE 14-11 An ECG tracing showing a sinus mechanism with one (+) P for each QRS. However, not all the P waves are similar. In fact, there appear to be premature QRS complexes, each with a premature P′ wave, creating a pattern; every other beat is an ectopic. When every other beat is an ectopic, this is *bigeminy*. In this case, the ectopic has its origin in the atria. Thus, the ECG interpretation would be sinus rhythm at 86 bpm with *atrial bigeminy*.



Atrial Tachycardia

Atrial tachycardia is present when an atrial ectopic focus depolarizes the atria at a rate of 130 to 250 bpm. Generally, the AV node delays many of the atrial ectopic beats and the resulting ventricular rate is usually normal. The ventricular rhythm may be regular or irregular. When atrial tachycardia appears suddenly and then disappears moments later, it is referred to as **paroxysmal atrial tachycardia**. The ECG characteristics of atrial tachycardia in lead II are as follows:

- **P′ wave:** Starts abruptly, at rates of 130 to 250 bpm. The P′ wave may or may not be seen. Visible P′ waves differ in configuration from the normal sinus P wave. At more rapid rates, the P′ is hidden in the preceding T wave and cannot be seen as a separate entity.
- **P′R interval:** The PR interval has a normal duration between 0.12 and 0.20 second and is constant from beat to beat. The P′R interval is difficult to measure at rapid rates.
- **QRS complex:** The QRS complex duration is 0.12 second or less. A P wave usually precedes every QRS complex, although a 2:1 AV conduction ratio is often seen. The QRS complexes during atrial tachycardia may be normal or abnormal, depending on the degree of ventricular refractoriness and AV conduction time.
- **QRS rate:** Very regular.
- **QRS rhythm:** Atrial tachycardia begins suddenly and is very regular.

Figure 14–12 shows an example of atrial tachycardia. Figure 14–13 shows an example of paroxysmal atrial tachycardia.

FIGURE 14-12 An example of the onset of atrial tachycardia. In the beginning, the tracing shows a sinus rhythm at 100 bpm. A PAC (arrow) begins the sudden change in rate at 188 bpm.

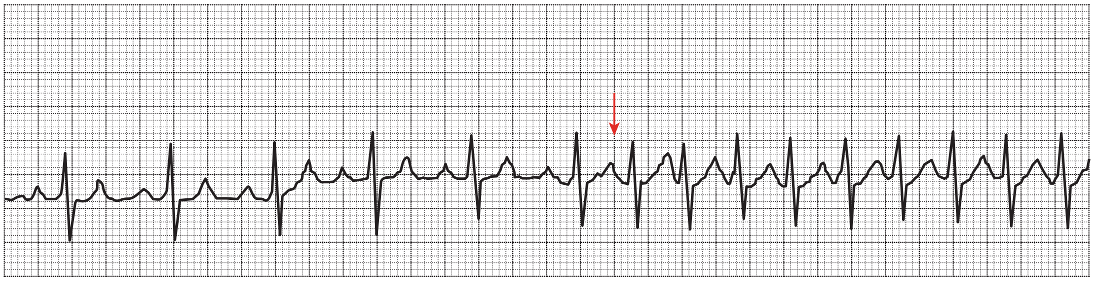
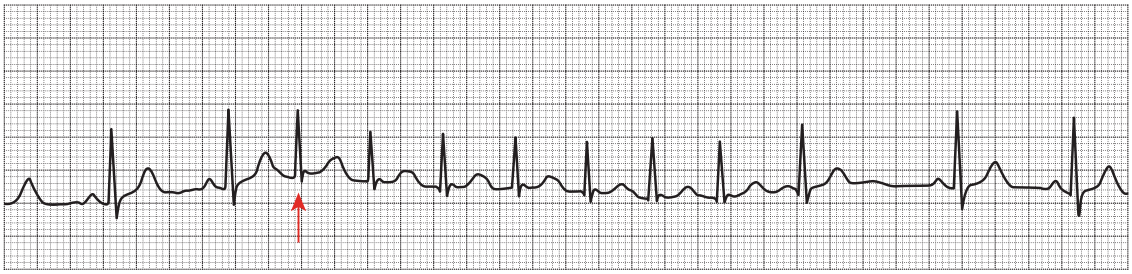


FIGURE 14-13 An ECG tracing showing a narrow QRS complex of similar configuration throughout. Plotting out the P waves, the atrial rate is 86 bpm for the first two complexes. The rate changes suddenly. Note the PAC (arrow) at the beginning of the tachycardia. The rate here is 136 bpm, and T waves are distorted and lumpy, indicating the atrial ectopics. The rate changes again, beginning with a pause and reverting to a sinus rhythm. The visible sudden onset and end of the tachycardia is called *paroxysm*. The identification is sinus at 86 → atrial tachycardia (PAT) at 136 per minute → sinus at 86 per minute. The sinus P waves do not plot through this event.



Atrial tachycardia is associated with conditions that stimulate the sympathetic nervous system, such as anxiety, excessive ingestion of caffeine or alcohol, and smoking. Unlike sinus tachycardia, which generally goes unnoticed by the patient, the patient "feels" the sudden onset of atrial tachycardia. Young adults sometimes have sudden periods of paroxysmal atrial tachycardia. Atrial tachycardia is also associated with the early stages of menopause.

Atrial Flutter

A consequence of PACs is the development of *atrial flutter.* In atrial flutter, the normal P wave is absent and replaced by two or more regular sawtooth-like waves, called *flutter or ff waves.* The QRS complex is normal and the ventricular rate may be regular or irregular, depending on the relationship of the atrial to ventricular beats. Figure 14–14 shows an atrial flutter with a regular rhythm and with a 4:1 conduction ratio (i.e., four atrial beats for every ventricular beat). Usually, the atrial rate is constant between 200 and 300 bpm, whereas the ventricular rate is in the normal range. The ECG characteristics of atrial flutter in lead II are as follows:

- **ff waves:** Atrial depolarization is regular. Commonly has a sawtooth-like or sharktooth-like appearance.
- **P′R interval:** The P′R interval of the ff waves is typically 0.24 to 0.40 second and consistent with the QRS complex.
- **QRS complex:** The QRS complex duration is usually 0.12 second or less. Depending on the degree of ventricular refractoriness, the QRS may be greater than 0.12 second. When this is the case, the ff waves distort the QRS complexes and T waves.
- **QRS rate:** The QRS rate is a function of the degree of ventricular refractoriness and of the AV conduction time.
- **QRS rhythm:** Depending on AV conduction, the QRS rhythm may be regular or irregular.

Figure 14–15 shows three different examples of atrial flutter.

Atrial flutter is frequently seen in patients over 40 years of age with COPD (e.g., emphysema, chronic bronchitis), chronic heart disease (e.g., congestive heart failure, valvular heart disease), chronic hypertension, myocardial ischemia, myocardial infarction, hypoxemia, quinidine excess, pulmonary embolus, and hepatic disease.

Atrial Fibrillation

Another consequence of PACs is the development of *atrial fibrillation,* which is a chaotic, disorganized, and ineffective state occurring within the atria. During atrial fibrillation, the AV node is bombarded by hundreds of atrial ectopic impulses at various rates and amplitudes. Atrial fibrillation is usually easy to identify and is often referred to as *coarse fibrillation*. Unlike atrial flutter, atrial fibrillation is commonly seen in the clinical setting. The atrial rate cannot be measured because it often reaches rates between 300 and 600 bpm.

FIGURE 14-14 Atrial flutter with a 4:1 conduction ratio.

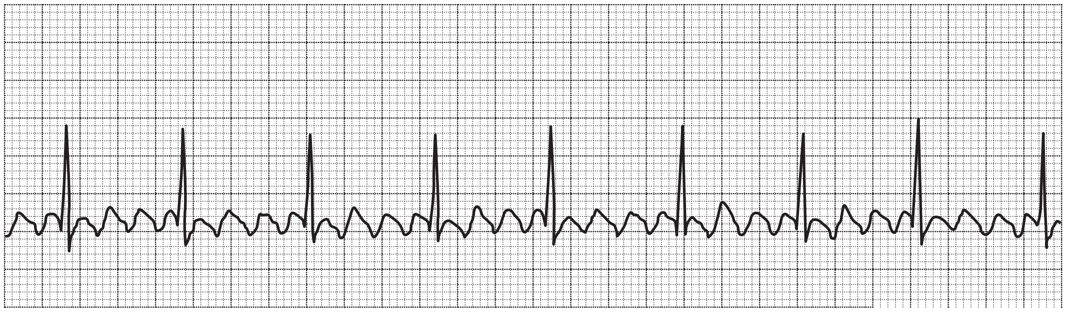
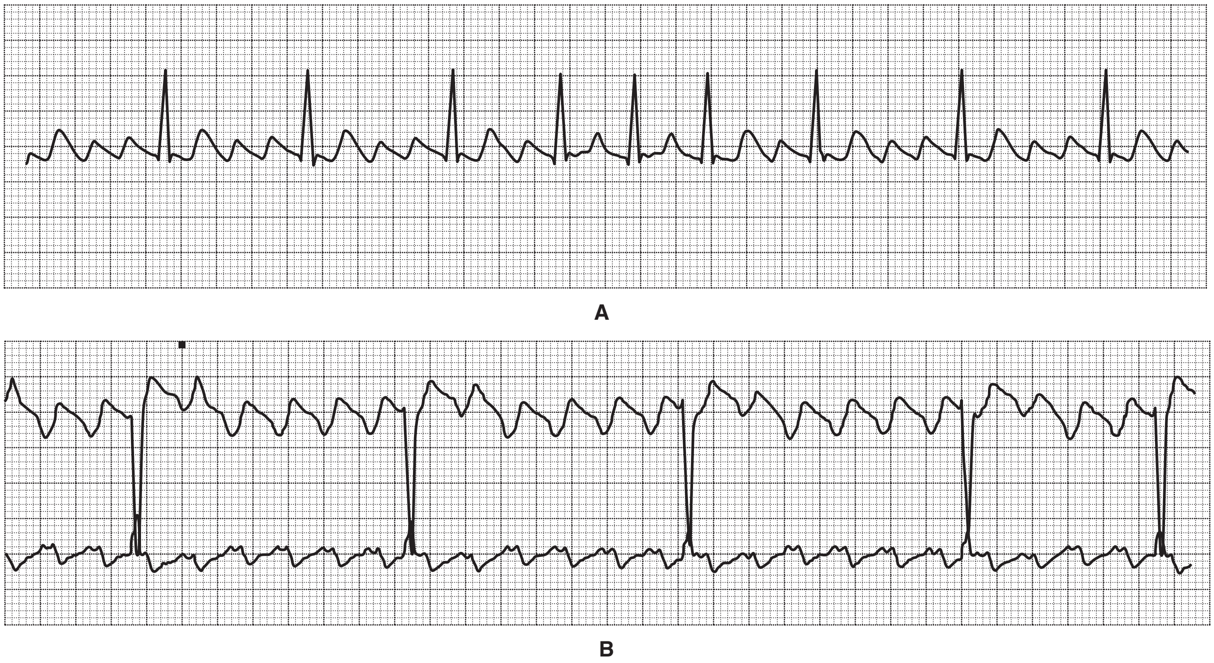


FIGURE 14-15 **A.** ECG showing new-onset atrial flutter in a patient. **B.** A continuous ECG tracing from a patient with recurrent atrial flutter. The patient was taking lanoxin 0.25 mg daily for 37 days.

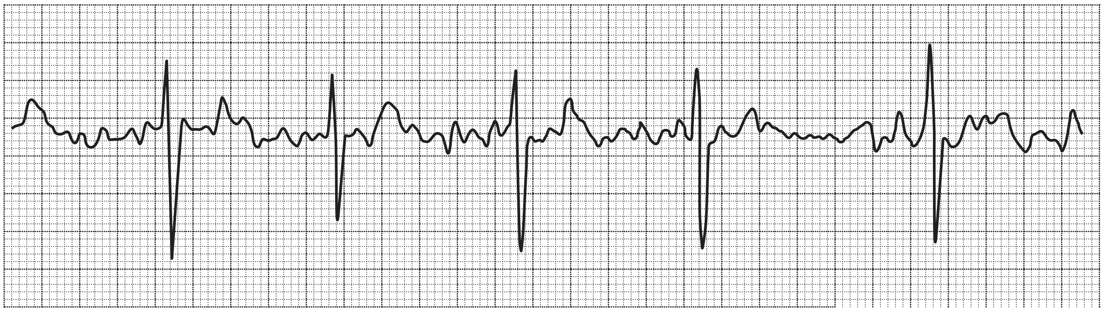


The atrial P′ waves are called *fib* or *ff* waves. Atrial fibrillation may reduce the cardiac output by as much as 20 percent because of the atrial quivering and loss of atrial filling (the so-called atrial kick). The characteristics of atrial fibrillation seen on ECG are as follows:

- **ff waves:** Atrial depolarization is chaotic and irregular.
- **PR interval:** There are no PR intervals.
- **QRS complex:** The QRS complex duration is usually 0.12 second or less. The ff waves often distort the QRS complexes and T waves.
- **QRS rate:** The QRS rate is a function of the degree of ventricular refractoriness and conduction time.
- **QRS rhythm:** Depending on AV conduction, the QRS rhythm may be regular or irregular.

Figure 14–16 shows an example of atrial fibrillation with an irregular QRS rhythm.

FIGURE 14-16 ECG tracing showing narrow QRS complex with an irregular rhythm. The chaotic pattern between the QRS complexes is the atrial fibrillation. This coarse pattern is easily seen.



Atrial fibrillation is associated with COPD, valvular heart disease, congestive heart failure, ischemic heart disease, and hypertensive heart disorders. Paroxysmal atrial fibrillation may also occur as a result of emotional stress, excessive alcohol consumption, and excessive straining and vomiting.

Ventricular Mechanisms

Premature Ventricular Contraction

A *premature ventricular contraction* (PVC) is the result of abnormal electrical activity arising within the ventricles. The QRS complex is not preceded by a P wave; rather it is wide, bizarre, and unlike the normal QRS complex. The QRS has an increased amplitude with a T wave of opposite polarity; that is, a positive QRS complex is followed by a negative T wave. The characteristics of a PVC seen on ECG are as follows:

- **P wave:** There is no P wave before a PVC. The P waves of the dominant rhythm are normal.
- **PR interval:** There is no PR interval before a PVC. The PR interval of the dominant rhythm is normal.
- **QRS complex:** The QRS complex is wide (long duration), bizarre, and unlike the normal QRS complex. The QRS of the PVC usually has an increased amplitude with a T wave of opposite polarity. The QRS-T may also present with diminished amplitude and be narrow (short duration).
- **QRS rate:** The QRS rate is that of the underlying rhythm.
- **QRS rhythm:** The rhythm is that of the underlying rhythm, and PVCs disturb the regularity.

Figure 14–17 shows an ECG tracing with a PVC.

PVCs may occur in various forms, including **uniform PVCs**, **multiform PVCs**, **paired PVCs**, **bigeminal PVCs**, and **trigeminal PVCs**. *Uniform PVCs* (also called unifocal) originate from one focus. All the PVCs on an ECG tracing are similar in appearance, size, and amplitude (see Figure 14–17). *Multiform PVCs* (also called multifocal) originate from more than one focus. When this occurs, the PVCs take on different shapes and amplitudes (Figure 14–18). *Paired PVCs* (also called couplets) are two closely coupled PVCs in a row. Paired PVCs are dangerous because the second PVC can occur when the ventricle is refractory and may cause ventricular fibrillation (Figure 14–19). Ventricular *bigeminy* is a PVC that occurs every other beat (i.e., a normal sinus beat, PVC, sinus beat, PVC, etc.) (Figure 14–20). Ventricular *bigeminy* is often seen in patients receiving digitalis. *Trigeminy* occurs when every third beat is a PVC (see Figure 14–21).

Common causes of PVCs include intrinsic myocardial disease, electrolyte disturbances (e.g., hypokalemia), hypoxemia, acidemia, hypertension, hypovolemia, stress, and congestive heart failure. PVCs may

FIGURE 14-17 An ECG tracing of rhythm and two premature ventricular complexes (PVCs). Note the difference in morphology in the QRS complexes: The QRS of the premature complex is different from the dominant QRS complexes because it does not use the ventricular conduction pathways. The premature ventricular QRS is opposite from its T wave. The sinus P waves plot through the events because sinus cadence is undisturbed. The PVCs are similar to each other and are *uniform* in appearance. The ECG interpretation would be sinus rhythm at 86 bpm with frequent, uniform PVCs.

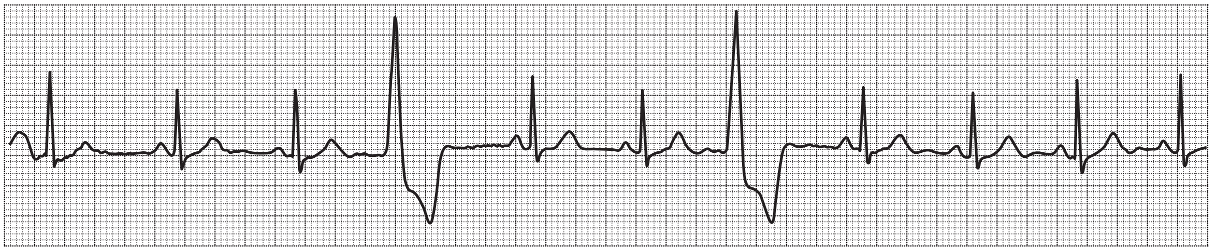


FIGURE 14-18 Note the difference between the PVCs. The ECG interpretation would be sinus rhythm about 78 bpm with frequent, *multiformed* PVCs.

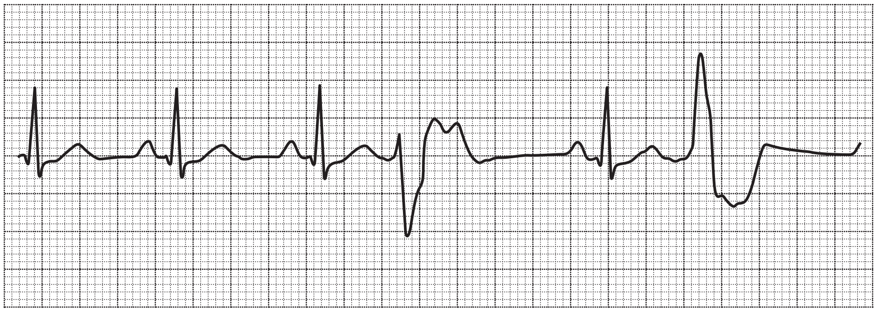


FIGURE 14-19 An ECG tracing showing sinus rhythm with frequent, uniform PVCs and two examples of *paired* PVCs or *couplets*. Couplets indicate the beginning of reentry and are regarded as dangerous.

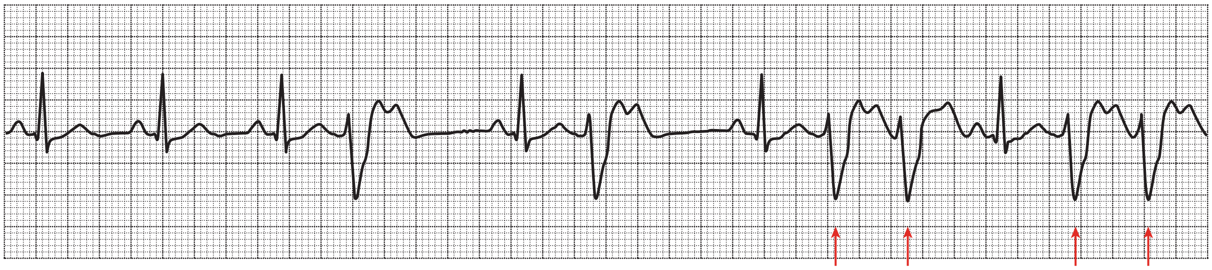


FIGURE 14-20 ECG tracing illustrating ventricular *bigeminy* (every other complex is a PVC).

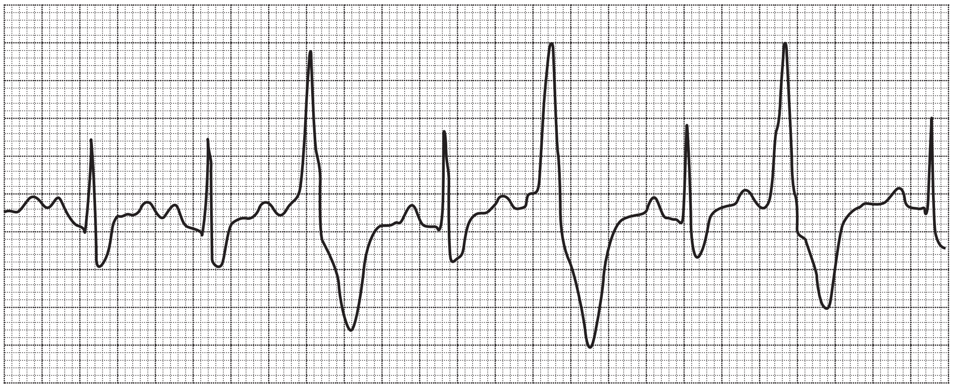
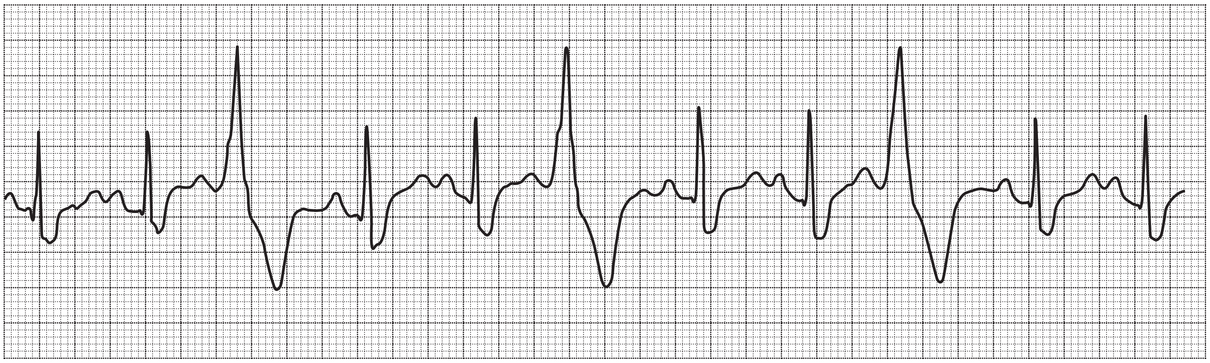


FIGURE 14-21 ECG tracing illustrating *trigeminy* (every third complex is a PVC).



also develop as a result of use of caffeine or certain medications such as digitalis, isoproterenol, dopamine, and epinephrine. PVCs may also be a sign of theophylline, alpha-agonist, or beta-agonist toxicity.

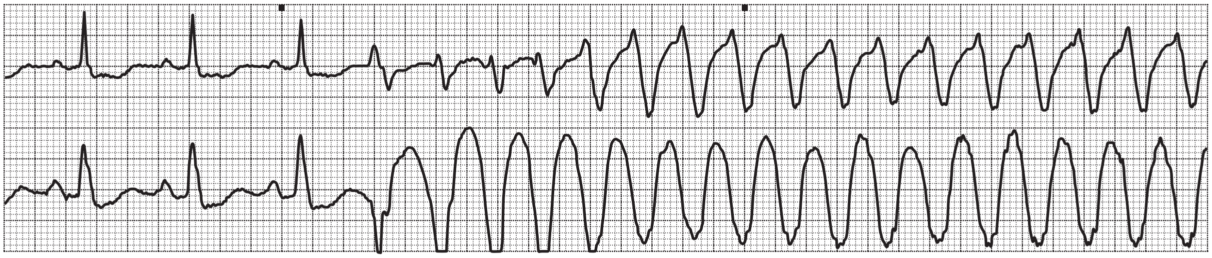
Ventricular Tachycardia

Three or more PVCs occurring in a row represent *ventricular tachycardia*. The QRS complex is wide and bizarre in appearance, making it difficult or impossible to identify the P and T waves. The rate is regular, or slightly irregular, between 100 and 170 bpm. Ventricular tachycardia is often initiated by a PVC that is significantly premature, although it may occur suddenly after a normal sinus rhythm. When ventricular tachycardia appears suddenly and then disappears moments later, it is referred to as **paroxysmal** or **intermittent** ventricular tachycardia. When the ECG tracing shows only ventricular tachycardia, it is called *sustained ventricular tachycardia* or *V-tach*. The blood pressure level is often decreased during ventricular tachycardia. The characteristics of ventricular tachycardia seen on ECG are as follows:

- **P wave:** The P wave usually cannot be identified during ventricular tachycardia.
- **PR interval:** The PR interval cannot be measured.
- **QRS complex:** The QRS duration is usually greater than 0.12 second and bizarre in appearance. The T wave usually cannot be identified.
- **QRS rate:** Between 100 and 170 bpm. Three or more consecutive PVCs constitute ventricular tachycardia.
- **QRS rhythm:** Regular or slightly irregular.

Figure 14–22 shows an ECG tracing of ventricular tachycardia.

FIGURE 14-22 An ECG tracing from a 55-year-old patient with ventricular tachycardia. The patient responded to antiarrhythmic medication and was reportedly successfully reperfused.



Clinical Connection 14-2

Pulseless Arrest: ACLS* Treatment Protocol

The **pulseless arrest algorithm** is the most important algorithm in the ACLS Protocol. The following four dysrhythmias produce a pulseless arrest:

- Pulseless ventricular tachycardia (VT)
- Ventricular fibrillation (VF)
- Asystole
- Pulseless electrical activity (PEA)

The ACLS provides the following two pathways in the pulseless arrest algorithm: (1) VF/VT pathway and (2) asystole/PEA pathway. See Clinical Connection 14–3: Ventricular Fibrillation and Pulseless Ventricular Tachycardia and Clinical Connection 14–4: Asystole and Pulseless Electrical Activity later in this chapter for these two treatment protocol pathways.

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*Advanced Cardiac Life Support (http://acls-algorithms.com).

Ventricular Flutter

In ventricular flutter, the ECG shows poorly defined QRS complexes. The rhythm is regular or slightly irregular, and the rate is 250 to 350 bpm. Ventricular flutter is rarely seen in the clinical setting because it usually deteriorates quickly into ventricular fibrillation. There is usually no discernible peripheral pulse. The characteristics of ventricular flutter seen on ECG are as follows:

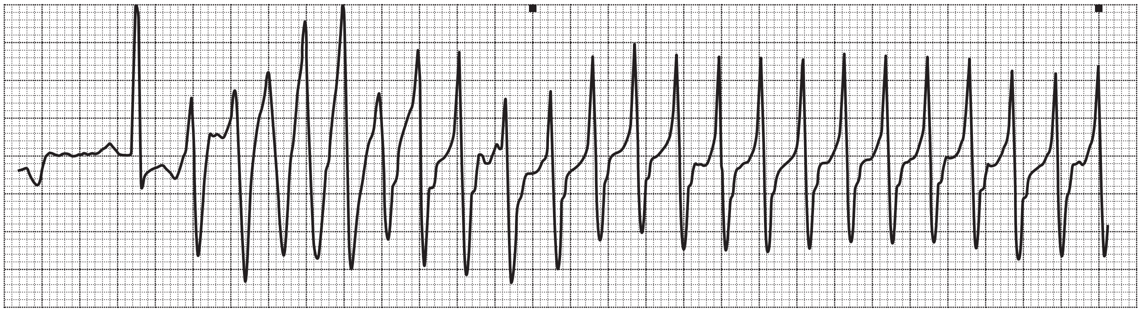
- **P wave:** The P wave is usually not distinguishable.
- **PR interval:** The PR interval is not measurable.
- **QRS complex:** The QRS duration is usually greater than 0.12 second and bizarre in appearance. The T wave is usually not separated from the QRS complex.
- **QRS rate:** Between 250 and 350 bpm.
- **QRS rhythm:** Regular or slightly irregular.

Figure 14–23 shows an ECG tracing of ventricular flutter.

Ventricular Fibrillation

Ventricular fibrillation is characterized by multiple and chaotic electrical activities of the ventricles. The ventricles literally quiver out of control with no beat-producing rhythm. Ventricular fibrillation is a terminal

FIGURE 14-23 An ECG tracing showing a sinus beat followed by an R-on-T PVC, which caused ventricular flutter as confirmed on a 12-lead ECG.

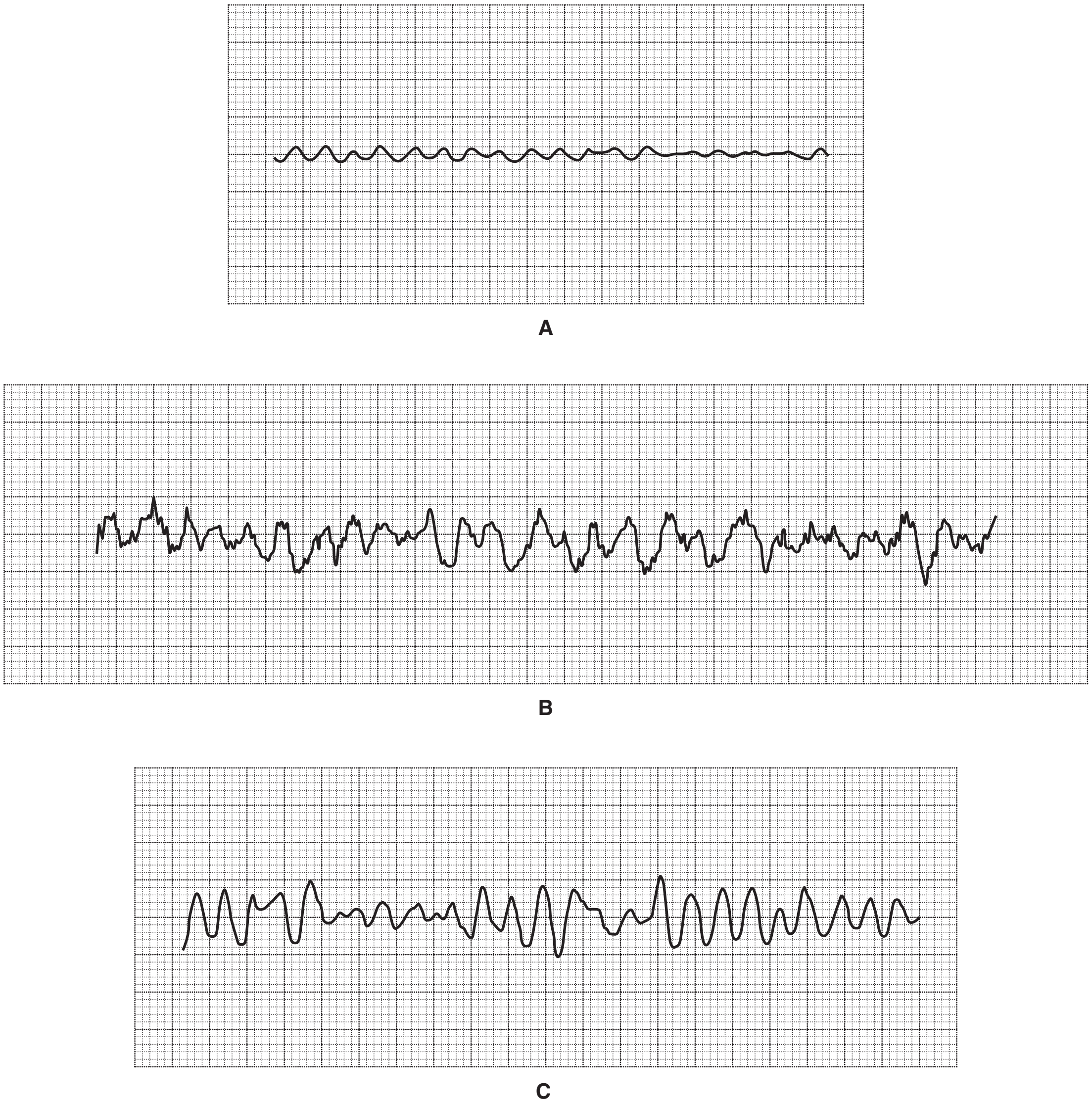


rhythm. It may follow PVCs, ventricular tachycardia, and ventricular flutter. During ventricular fibrillation, there is no cardiac output or blood pressure and, without treatment (defibrillation), the patient will die in minutes. The characteristics of ventricular fibrillation seen on ECG are as follows:

- **P wave:** The P waves cannot be identified.
- **PR interval:** The PR interval is not measurable.
- **QRS complex:** The QRS complex cannot be identified.
- **QRS rate:** A rate cannot be calculated.
- **QRS rhythm:** The rhythm is chaotic because of multiple, disorganized ventricular contractions.

Figure 14–24 shows three different examples of ventricular fibrillation.

FIGURE 14-24 ECG tracings from three patients with ventricular fibrillation.



Clinical Connection 14-3

Ventricular Fibrillation and Pulseless Ventricular Tachycardia: ACLS* Treatment Protocol

Ventricular fibrillation and pulseless ventricular tachycardia are shockable rhythms. **High-quality CPR** should be performed until the defibrillator is attached to the patient. Rapid use of the defibrillator should be emphasized in the treatment of these rhythms.

Defibrillation: Rapid use of the defibrillator is emphasized in ACLS protocols. Manual defibrillators are preferred over an automated external defibrillator (AED) if possible—because the use of an AED often interrupts high-quality CPP while it performs rhythm analysis and shock administration. The dose in joules will be determined based on the individual circumstances of each patient.

Vasopressors: Vasopressor agents are used to produce vasoconstriction and to increase blood pressure. **Epinephrine** is primarily used for its vasoconstrictive effects. During CPR, epinephrine is commonly used to help increase blood flow to the brain and heart. Vasopressin is also used for its vasoconstrictive effects and has been shown to have effects similar to those of epinephrine.

Anti-dysrhythmic drugs: Amiodarone, Lidocaine, and **magnesium** are used for their anti-dysrhythmic effects. Amiodarone is used for a wide variety of atrial and ventricular tachy dysrhythmias and for rate control of rapid atrial dysrhythmias. Lidocaine can be given via tracheal tube for stable ventricular tachycardia. Magnesium is used for ventricular fibrillation.

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*Advanced Cardiac Life Support (http://acls-algorithms.com).

Asystole (Cardiac Standstill)

Asystole is the complete absence of electrical and mechanical activity. As a result, the cardiac output stops and the blood pressure falls to about 5 to 7 mm Hg. The ECG tracing appears as a flat line and indicates severe damage to the heart's electrical conduction system (Figure 14–25). Occasionally, periods of disorganized electrical and mechanical activity may be generated during long periods of asystole; this is referred to as an *agonal rhythm* or a *dying heart.*

Clinical Connection 14-4

Asystole and Pulseless Electrical Activity: ACLS* Treatment Protocol

Asystole is defined as a cardiac arrest rhythm in which there is no discernible electrical activity on the ECG monitor. Asystole and pulseless electrical activity (PEA) are not shockable rhythms. Provide high-quality CPR, while other team members establish IV or IO (intraosseous infusion—the process of injecting fluid or medication directly into the marrow of the bone) access. Of course, attention should be given to evaluating and treating reversible causes of these rhythms.

Asystole is sometimes referred to as a "flat line." Treatment protocol is:

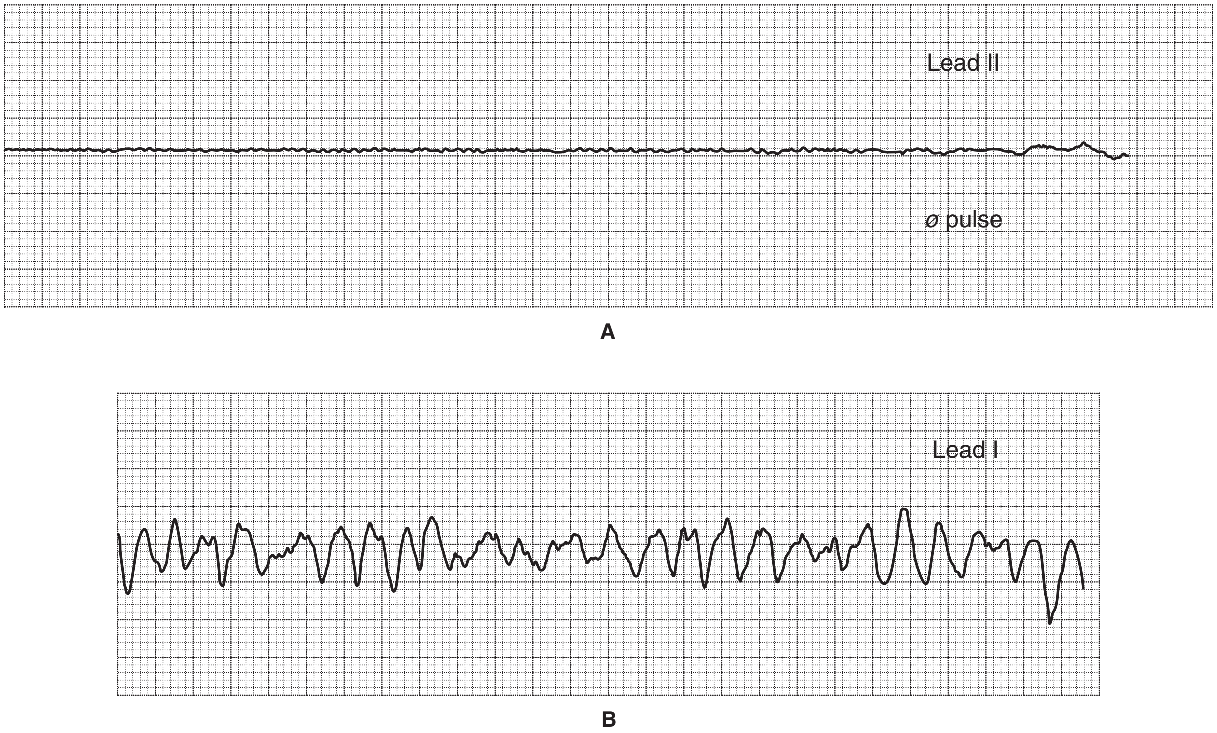
Epinephrine: Used for cardiac arrests—ventricular fibrillation, pulseless ventricular tachycardia, asystole, and pulseless electrical activity.

Vasopressin: Used as an alternative pressor to epinephrine.

Note: Atropine has been removed from the algorithm per 2010 ACLS Guidelines.

*Advanced Cardiac Life Support (http://acls-algorithms.com).

FIGURE 14–25 ECG tracings from the same patient: **(A)** an apparent asystole or fine ventricular fibrillation; **(B)** ventricular fibrillation confirmed on lead I.



AV Conduction Defects

Sinus Rhythm with First-Degree AV Block

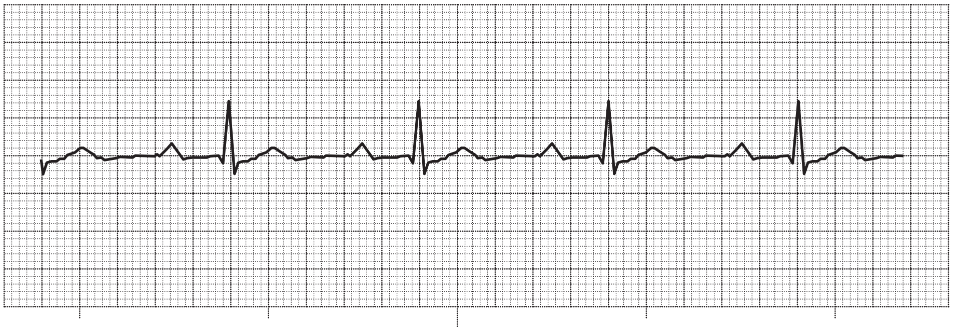
When the atrial impulse is delayed as it moves through the AV node, the PR interval increases. When the PR interval is consistently greater than 0.20 second, a *first-degree AV block* is said to exist. The ECG characteristics of first-degree AV block in lead II are as follows:

- **P wave:** The P waves are positive and uniform. Each P wave is followed by a QRS complex.
- **PR interval:** The PR interval is consistently greater than 0.20 second from beat to beat.
- **QRS complex:** The duration of the QRS complex is 0.12 second or less. Each QRS complex is preceded by a P wave.
- **QRS rate:** The rate is usually based on the normal sinus rhythm and is constant between 60 and 100 bpm.
- **QRS rhythm:** The rhythm is dependent on the sinus rhythm. When a sinus dysrhythmia is present, the rhythm will vary accordingly.

Figure 14–26 shows a first-degree AV block. Note that the only variation from a normal sinus rhythm is the prolonged PR interval.

Causes of first-degree AV block include right coronary artery disease, endocarditis, myocarditis, electrolyte disturbances, and aging.

FIGURE 14-26 An ECG tracing illustrating a sinus rhythm at 60 bpm with a consistently prolonged PR interval that is greater than 0.20 second. Note that the PR segment is greater than 0.12 second. The ECG interpretation would be sinus rhythm at 60 bpm with first-degree AV block.



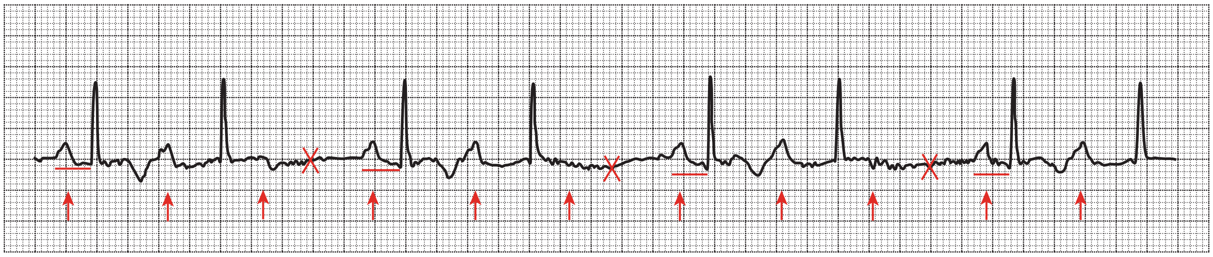
Sinus Rhythm with Second-Degree AV Block: The Wenckebach Phenomenon

The **Wenckebach phenomenon** is a progressive delay in the conduction of the atrial impulse through the AV junction until, eventually, an atrial impulse is completely blocked from the ventricles. In other words, in a sinus rhythm, progressive lengthening of the PR segment occurs until a P wave is not conducted. This is because the progressive prolongation of the PR interval ultimately causes the P wave to occur during the refractory period of the ventricles, resulting in a missed QRS complex. The next P wave occurs right on time. The first PR interval immediately after the missed QRS complex is the first PR interval of the next Wenckebach cycle. The Wenckebach phenomenon may repeat itself with variations in the number of conducted beats. The characteristics of the Wenckebach phenomenon seen on ECG are as follows:

- Progressive prolongation of the PR interval.
- The complex Wenckebach cycle begins and ends with a P wave.
- There is one more P wave than QRS complexes in a cycle.
- Irregular or decreasing RR intervals.

Figure 14–27 shows an ECG tracing of the Wenckebach phenomenon.

FIGURE 14-27 An ECG tracing showing progressive prolongation of the PR interval until the sinus P wave does not conduct into the ventricles. There is no ventricular depolarization, hence the missed QRS. The PR after the dropped beat is consistent with each instance. The ECG interpretation would be sinus rhythm at 86 bpm with second-degree AV block, Wenckebach, probably type I (QRS 0.08 second) inverted T waves, and ventricular rate 57 to 75 bpm. Red arrows are pointing to the P waves.



Complete AV Block

When the pathology of the AV junction is severe, all the sinus impulses may be blocked. When a **complete AV block** is present, the *bundle of His* takes control of the ventricular rhythm at a rate of 40 to 60 bpm. This mechanism is referred to as the *escape junctional pacemaker.* The ventricular rhythm is regular. The sinus rhythm continues at its normal rate (60 to 100 bpm), completely independent of the ventricular rhythm. The sinus rhythm is regular.

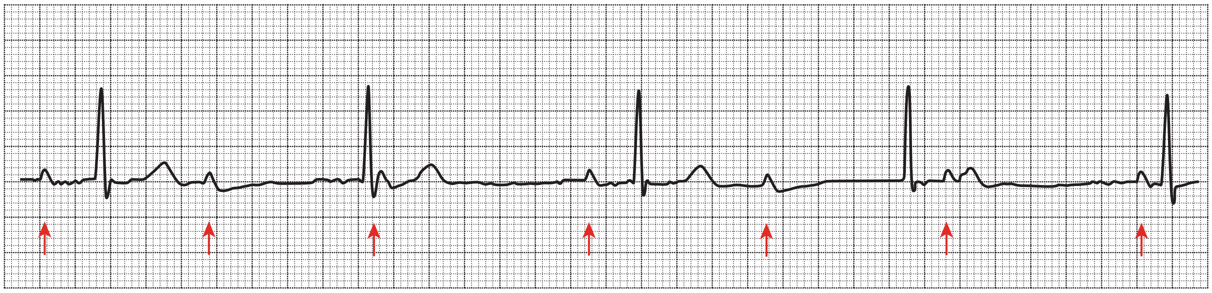
When the complete AV block is caused by pathology below the bundle of His, the ventricular rhythm is controlled by what is called a ventricular escape mechanism. The rate of the ventricular escape mechanism is between 20 and 40 bpm. Similar to complete AV block above the bundle of His, the atrial and ventricular rates will be independent of each other and regular in rhythm.

To summarize, in complete AV block, the atrial rate is faster and completely independent of the ventricular rate. There is no relationship between the P and QRS complexes, and there are no PR intervals. The atria remain under the control of the SA node, and the ventricles are under the control of the bundle of His or of a ventricular escape mechanism. The ECG characteristics of complete AV block in lead II are as follows:

- **P wave:** The P waves are positive and uniform. There is no relationship between the P waves and the QRS complexes. The atrial rate is faster than the ventricular escape rate.
- **PR interval:** There are no measurable PR intervals because there is no relationship between the P waves and QRS complexes.
- **QRS complex:** The duration of the QRS complex may be normal or greater than 0.12 second. When the pathology is above the bundle of His, the QRS complex is usually normal (<0.12 second). When the pathology is below the bundle of His, the duration of the QRS complexes will be greater than 0.12 second.
- **QRS rate:** The atrial rate is faster and completely independent of the ventricular rate. A junctional escape pacemaker produces a rate between 40 and 60 bpm. A ventricular escape pacemaker produces a rate between 20 and 40 bpm.
- **QRS rhythm:** Both a junctional escape pacemaker and a ventricular escape pacemaker produce a regular rhythm.

Figure 14–28 shows an ECG tracing with complete AV block.

FIGURE 14-28 An ECG illustrating complete AV block, probably at the level of the AV node because the QRS is 0.06 second. The atrial rate is faster than the QRS rate, and the P waves and QRS complexes are independent of each other. There are no consistent PR intervals. The ECG interpretation would be sinus rhythm at 50 bpm with complete AV block, a junctional rhythm with a ventricular rate at 40 bpm. Red arrows are pointing to the P waves.



Clinical Connection 14-5

Cardiac Pacemaker

What happens when there is an abnormality of the heart's intrinsic electrical conduction system? In some cases, the patient may be helped with a cardiac pacemaker. A pacemaker is a small device inserted in the chest or abdomen that discharges electrical impulses to assist the heart in maintaining a normal heart rhythm (Figure 14–29).

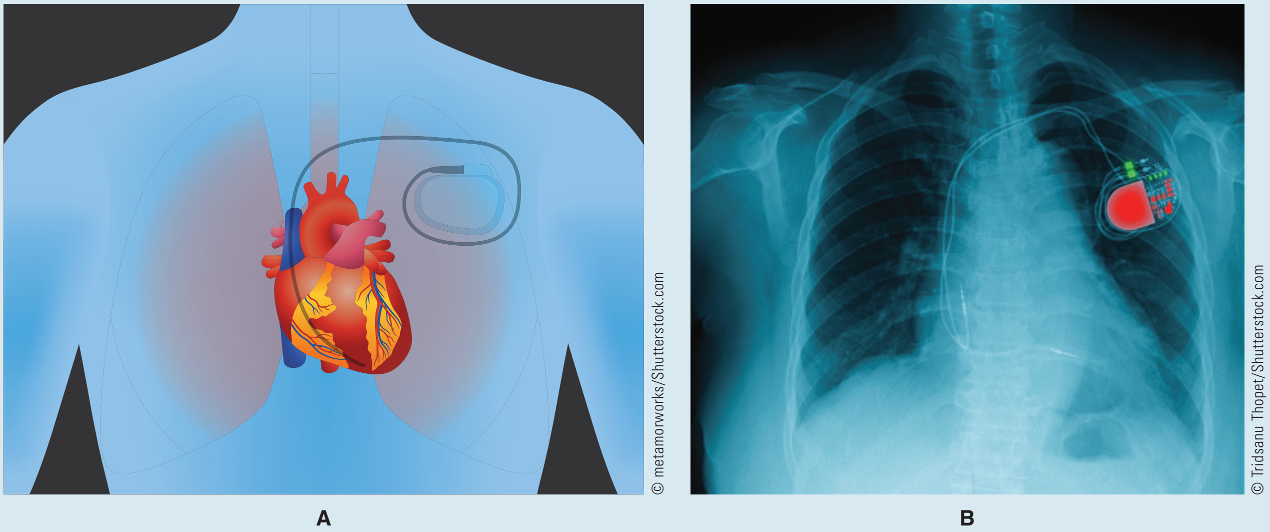
Either the atria, ventricles, or both may be paced depending on the patient's heart conduction abnormality. Atrial pacing is used when the sinus node fails to depolarize at all or at a lower than acceptable rate. Ventricular pacing may be used in cases of an atrial-ventricular block that prevents the wave of depolarization from reaching the ventricles. Some patients may have both the atria and ventricles paced. The specifics of the pacemaker are determined by the abnormalities within the conduction system for each patient.

Because the pacemaker is discharging an electrical stimulus, it can be observed directly on an ECG. The electrical discharge is termed a "pacemaker spike"—a short vertical mark on the ECG. An atrial pacemaker will generate a spike followed by a P wave and a normal QRS complex. Once the pacemaker fires an electrical stimulus, the wave of depolarization continues normally through the remainder of the electrical conduction network. With a ventricular pacemaker, a spike is seen before the QRS complex (Figure 14–30). When the pacemaker electrode is placed in the right ventricle, which then depolarizes first, followed by depolarization of the left ventricle, this creates a wide QRS complex like that seen in left bundle branch block.

When a sequential pacemaker is placed to depolarize both the atria and the ventricles, the pacemaker first depolarizes the atria and then the ventricles. With this type of pacing, two pacing spikes can be identified, the first before the P wave and the second occurring before the QRS complex.

While pacemakers and the patients underlying cardiac pathophysiology may be difficult to understand, it is important to be able to identify the electrical pacing spikes on an ECG. There are many complexities to the pacing that is delivered by the device as well as if the device isn't performing optimally with the patient's underlying electrical conduction system—failure to capture, failure to pace, etc. These require extensive training to understand and identify. However, the identification of the pacing spike is an important first step to understanding this medical device.

FIGURE 14-29 **A.** Graphic illustration of the position of a cardiac pacemaker. **B.** X-ray of cardiac pacemaker.



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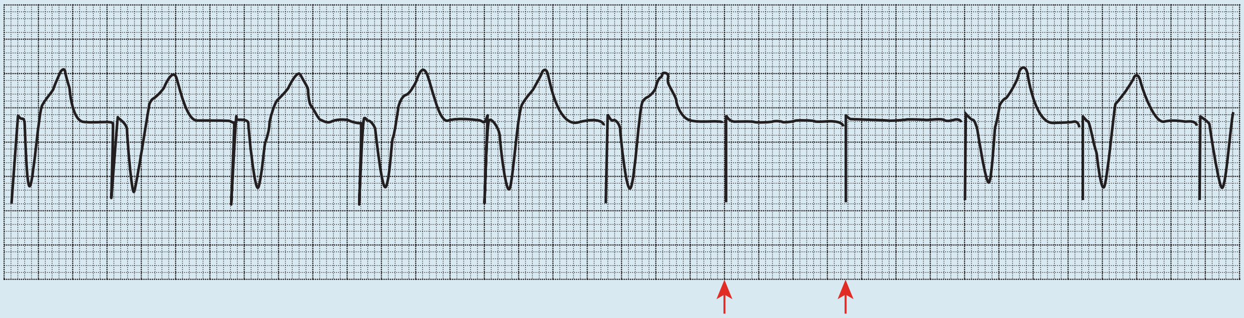
Clinical Connection 14-5, Continued

FIGURE 14-30 An ECG tracing of a ventricular paced rhythm with two episodes of failure to capture (arrows).



Chapter Summary

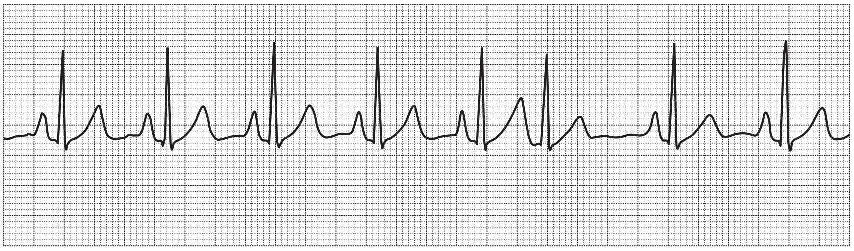
A consistent, systematic approach is fundamental to all good methods of ECG interpretation. This chapter presented a five-step systematic approach to ECG interpretation. *Step 1* is the *general inspection,* which requires the examiner to closely scan the ECG tracing to determine if the general appearance of the ECG tracing looks normal or abnormal. *Step 2* is the *analysis of ventricular activity* for rate, rhythm, and shape. *Step 3* is the *analysis of atrial activity* for rate, rhythm, and shape. *Step 4* is the *assessment of the atrioventricular relationship,* which includes the conduction ratio, discharge sequence, and PR interval. *Step 5* is the *ECG interpretation,* which determines if there is a normal sinus rhythm or cardiac dysrhythmias present.

The common cardiac dysrhythmias are the *sinus mechanisms,* which include sinus bradycardia, sinus tachycardia, sinus dysrhythmia, sinus block, and sinus arrest; the *atrial mechanisms,* which include premature atrial complex, atrial bigeminy, atrial tachycardia, atrial flutter, and atrial fibrillation; *ventricular mechanisms,* which include premature ventricular complex (PVC), uniform PVCs, multiform PVCs, paired PVCs, bigeminal PVCs, trigeminal PVCs, ventricular tachycardia, ventricular flutter, ventricular fibrillation, and asystole; and *AV conduction defects,* which include sinus rhythm with first-degree AV block, sinus rhythm with second-degree AV block, and complete AV block.

Clinical connections associated with this chapter include the ACLS treatment protocols for bradycardia, pulseless arrest, ventricular fibrillation and pulseless ventricular tachycardia, and asystole and pulseless electrical activity, as well as a discussion of cardiac pacemakers.

Review Questions

1.



QRS duration: ______________ QT duration: ______________

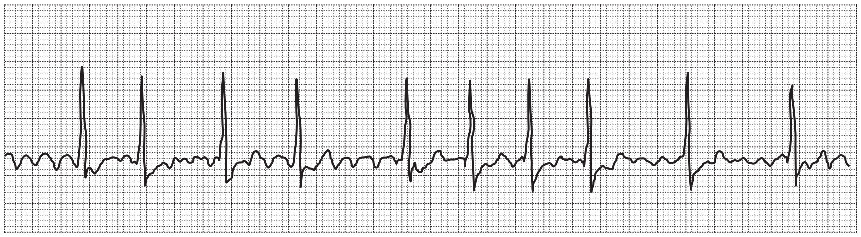
Ventricular rate and rhythm: ______________

Atrial rate and rhythm: ______________

PR interval: ______________

Interpretation: ______________

2.



QRS duration: ______________ QT duration: ______________

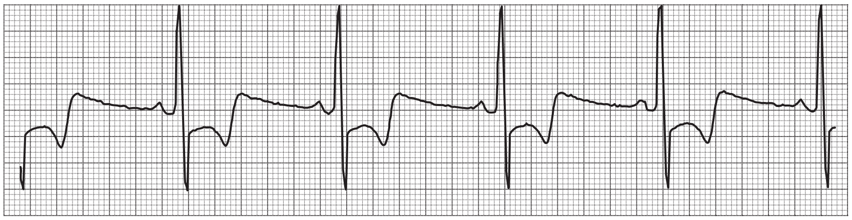
Ventricular rate and rhythm: ______________

Atrial rate and rhythm: ______________

PR interval: ______________

Interpretation: ______________

3.



QRS duration: ______________ QT duration: ______________

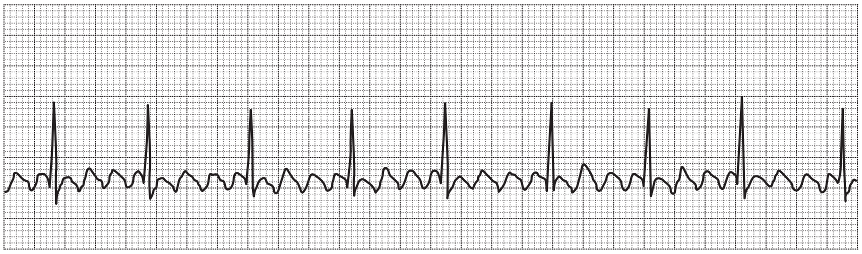
Ventricular rate and rhythm: ______________

Atrial rate and rhythm: ______________

PR interval: ______________

Interpretation: ______________

4.



QRS duration: ________ QT duration: ________

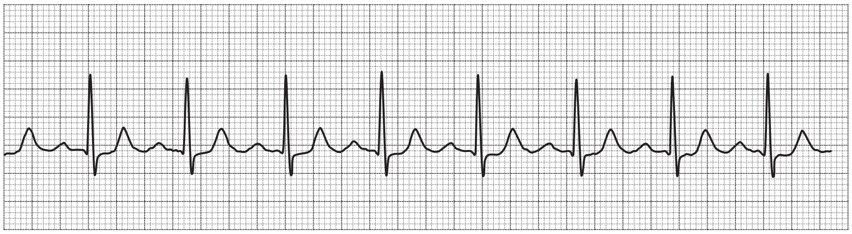
Ventricular rate and rhythm: ________

Atrial rate and rhythm: ________

PR interval: ________

Interpretation: ________

5.



QRS duration: ________ QT duration: ________

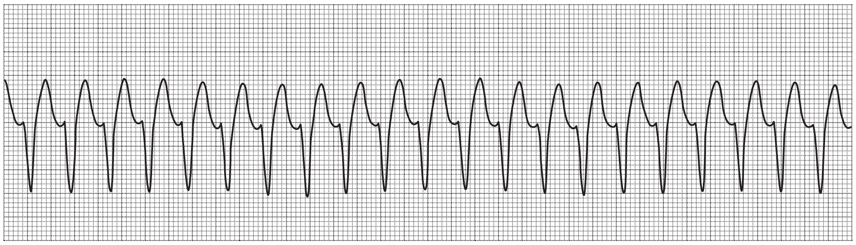
Ventricular rate and rhythm: ________

Atrial rate and rhythm: ________

PR interval: ________

Interpretation: ________

6.



QRS duration: ________ QT duration: ________

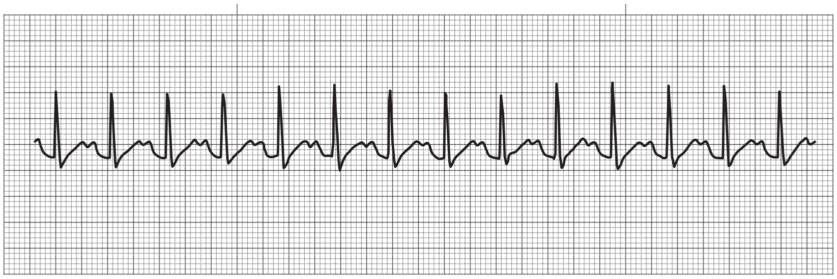
Ventricular rate and rhythm: ________

Atrial rate and rhythm: ________

PR interval: ________

Interpretation: ________

7.



QRS duration: ________________ QT duration: ________________

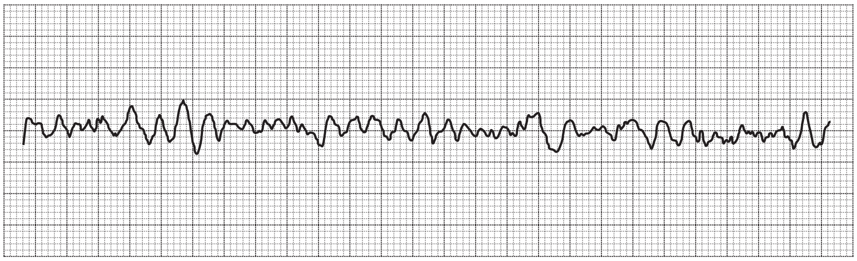
Ventricular rate and rhythm: ________________

Atrial rate and rhythm: ________________

PR interval: ________________

Interpretation: ________________

8.



QRS duration: ________________ QT duration: ________________

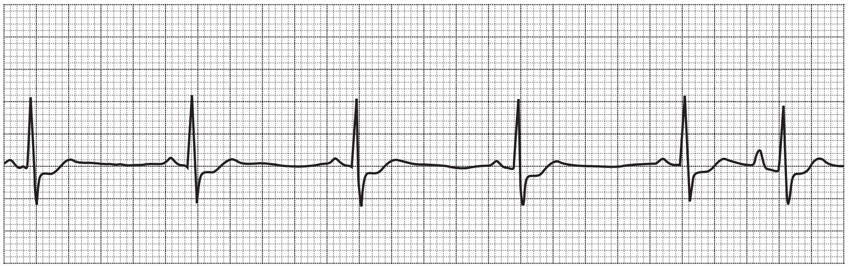
Ventricular rate and rhythm: ________________

Atrial rate and rhythm: ________________

PR interval: ________________

Interpretation: ________________

9.



QRS duration: ________________ QT duration: ________________

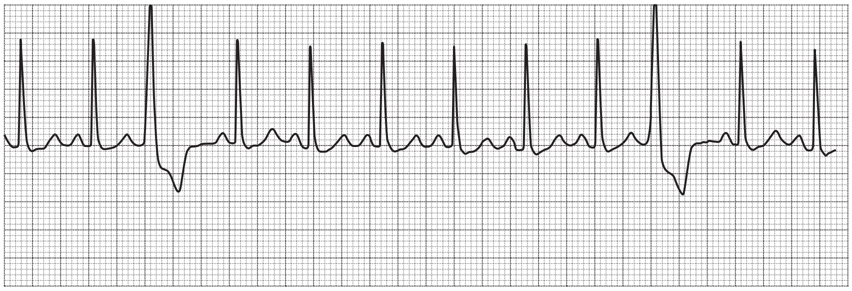
Ventricular rate and rhythm: ________________

Atrial rate and rhythm: ________________

PR interval: ________________

Interpretation: ________________

10.



QRS duration: ____________ QT duration: ____________

Ventricular rate and rhythm: ____________

Atrial rate and rhythm: ____________

PR interval: ____________

Interpretation: ____________

ЧСС
83
120
45
ARR
Взросл.
ПЖС/min
0
10
АД
167
106
69
ДЛА
33
21
14
CVP
15

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CHAPTER 15

Hemodynamic Measurements

OBJECTIVES

By the end of this chapter, the student should be able to:

1. List the abbreviations and normal ranges of the following hemodynamic values *directly* measured by means of the pulmonary artery catheter: central venous pressure, right atrial pressure, mean pulmonary artery pressure, pulmonary capillary wedge pressure, and cardiac output.
2. List the abbreviations and normal ranges of the following *computed* hemodynamic values: stroke volume, stroke volume index, cardiac index, right and left ventricular stroke work index, pulmonary vascular resistance, and systemic vascular resistance.
3. Explain the factors that increase and decrease stroke volume, stroke volume index, cardiac output, cardiac index, right ventricular stroke work index, and left ventricular stroke work index.
4. List the factors that increase and decrease the pulmonary vascular resistance.
5. List the factors that increase and decrease the systemic vascular resistance.

Hemodynamic Measurements

The term **hemodynamics** is defined as the study of the forces that influence the circulation of blood. With the advent of the **pulmonary artery catheter**[1] (PAC) (Figure 15–1), the hemodynamic status of the critically ill patient can be accurately determined at the bedside.[2] Clinically, the PAC is used for diagnostic purposes, to monitor therapy, and to assess the effects of drugs. In general, the PAC is able to obtain direct, simultaneous measurements of the pressures in the right atrium, right ventricle, and the filling pressure of the left atrium. The data generated can then be used to manage numerous hemodynamic problems—including hypovolemia, severe left ventricular failure, right ventricular infarction, and unstable angina.

In addition, the PAC can be used to collect data to make several patient-related critical assessments—including cardiogenic versus noncardiogenic pulmonary edema; primary versus secondary pulmonary hypertension; types of shock; fluid requirements; types of valvular heart disease; the presence of a cardiac tamponade; and the effects of therapy, such as afterload reduction, vasopressors, and beta blockers. As discussed in Chapter 6, the PAC can also be used to directly measure the oxygenation saturation of mixed-venous blood ($S\bar{v}O_2$) in the pulmonary artery. The continuous monitoring of $S\bar{v}O_2$ is often used in the clinical setting to detect changes in the patient's arterial-venous oxygen content difference [$C(a-\bar{v})O_2$], oxygen consumption ($\dot{V}O_2$), and oxygen extraction ratio (O_2ER).[3]

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[1] The PAC is often referred to as Swan–Ganz catheter in honor of its inventors Jeremy Swan and William Ganz.

[2] See Appendix V for a representative example of a cardiopulmonary profile sheet used to monitor the hemodynamic status of the critically ill patient.

[3] See Chapter 6, "Oxygen and Carbon Dioxide Transport."

FIGURE 15-1 Insertion of the pulmonary catheter. The insertion site of the pulmonary catheter may be the basilic, brachial, femoral, subclavian, or internal jugular veins. The latter two are the most common insertion sites. As the catheter advances, pressure readings and waveforms are monitored to determine the catheter's position as it moves through the right atrium (RA), right ventricle (RV), pulmonary artery (PA), and finally into a pulmonary capillary wedge pressure (PCWP) position. Immediately after a PCWP reading, the balloon is deflated to allow blood to flow past the tip of the catheter. When the balloon is deflated, the catheter continuously monitors the pulmonary artery pressure.

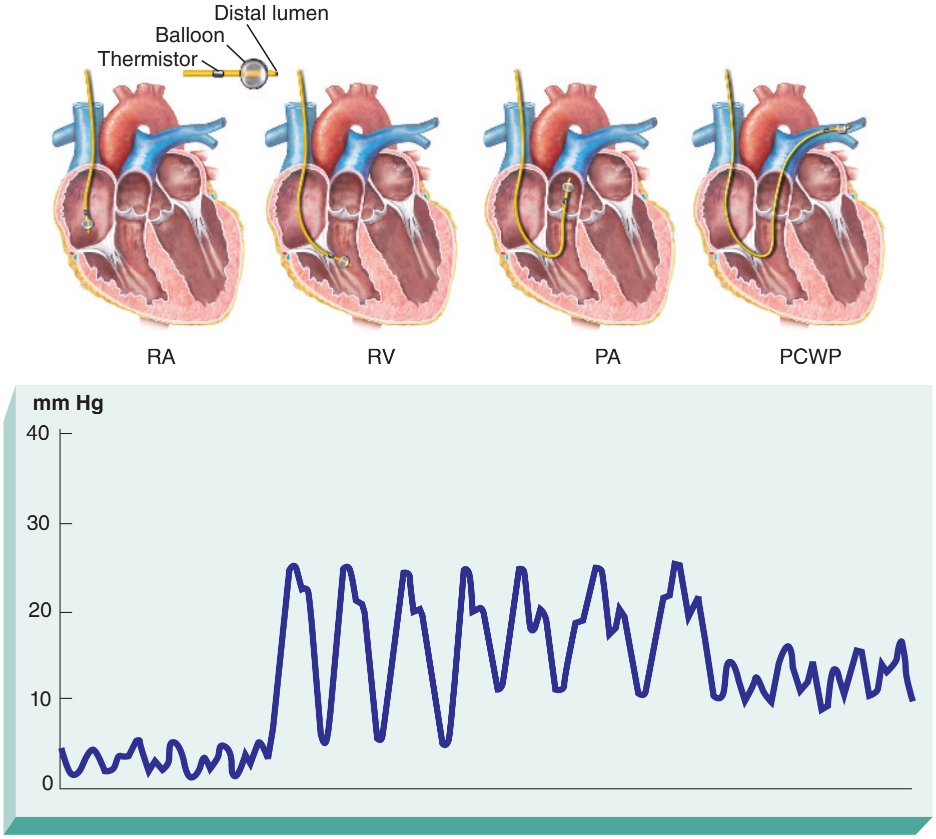

Table 15-1 provides the hemodynamic parameters that can be measured directly. Table 15–2 lists the major hemodynamic values that can be calculated from the direct measurements listed in Table 15–1. Today, such calculations are obtained either from a programmed calculator or by using the specific

TABLE 15-1 Hemodynamic Values Directly Obtained by Means of the Pulmonary Artery Catheter

Hemodynamic Value	Abbreviation	Normal Range
Central venous pressure	CVP	0–8 mm Hg
Right atrial pressure	RAP	0–8 mm Hg
Mean pulmonary artery pressure	$\overline{\text{PAP}}$	9–18 mm Hg
Pulmonary capillary wedge pressure (also pulmonary artery wedge; pulmonary artery occlusion)	PCWP PAW PAO	4–12 mm Hg
Cardiac output	CO	4–8 L/min

hemodynamic formula and a simple handheld calculator. Finally, because the hemodynamic parameters vary with the size of an individual, some hemodynamic values are "indexed" by body surface area (BSA). Clinically, the BSA is obtained from a height–weight nomogram (see Appendix IV). The normal adult BSA is 1.5 to 2 m^2.

TABLE 15-2 Computed Hemodynamic Values

Hemodynamic Value	Abbreviation	Normal Range
Stroke volume	SV	60–130 mL
Stroke volume index	SVI	30–65 mL/beat/m^2
Cardiac index	CI	2.5–4.2 L/min/m^2
Right ventricular stroke work index	RVSWI	7–12 g m/m^2
Left ventricular stroke work index	LVSWI	40–60 g m/m^2
Pulmonary vascular resistance	PVR	20–120 dynes × sec × cm^{-5}
Systemic vascular resistance	SVR	800–1500 dynes × sec × cm^{-5}

Clinical Connection 15-1

Case Study—The Adverse Effects of an Elevated Afterload on a Patient's Hemodynamic Parameters

In the Clinical Application Case 1 (page 493), the respiratory therapist is called to help care for a 71-year-old woman with sudden chest pain. This case illustrates how an elevated afterload can cause harmful changes in a patient's hemodynamic profile. For example, the patient's early hemodynamic profile shows a very high SVR and PCWP and a low CI,[4] which verifies the elevated afterload. The case further shows how the administration of nitroprusside can be used to correct an elevated afterload, and return the SVR, PCWP, and CI values back to normal.

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[4] SVR = systemic vascular resistance; PCWP = pulmonary capillary wedge pressure; CI = cardiac index.

Clinical Connection 15-2

Case Study—The Use of Best PEEP in Adjusting a Patient's Hemodynamic Profile

In the Clinical Application Case 2 (page 494), the respiratory therapist is called to help care for a 35-year-old man who was found unconscious, face down, in about 4 inches of water at a local beach. This case illustrates how the use of best level of **positive end-expiratory pressure (PEEP)**—commonly referred to as **best PEEP**—was the PEEP level that caused the least reduction of cardiac output and produced the maximum total oxygen delivery.

Hemodynamic Values Computed from Direct Measurements

Stroke Volume

The stroke volume (SV) is the volume of blood ejected by the ventricles with each contraction. The preload, afterload, and myocardial contractility are the major determinants of stroke volume. Stroke volume is derived by dividing the cardiac output (CO) by the heart rate (HR).

$$\mathrm{SV} = \frac{\mathrm{CO}}{\mathrm{HR}}$$

For example, if an individual has a cardiac output of 4.5 L/min (4500 mL/min) and a heart rate of 75 beats/min, the stroke volume would be calculated as follows:

$$\begin{aligned}\mathrm{SV} &= \frac{\mathrm{CO}}{\mathrm{HR}}\\ &= \frac{4500\ \mathrm{mL/min}}{75\ \mathrm{beats/min}}\\ &= 60\ \mathrm{mL/beat}\end{aligned}$$

Table 15–3 lists factors that increase and decrease the stroke volume.

TABLE 15-3 Factors Increasing and Decreasing Stroke Volume (SV), Stroke Volume Index (SVI), Cardiac Output (CO), Cardiac Index (CI), Right Ventricular Stroke Work Index (RVSWI), and Left Ventricular Stroke Work Index (LVSWI)

Increases	Decreases
Positive Inotropic Drugs (Increased Contractility)	**Negative Inotropic Drugs (Decreased Contractility)**
Dobutamine	Propranolol
Epinephrine	Timolol
Dopamine	Metoprolol
Isoproterenol	Atenolol
Digitalis	Nadolol
Amrinone	
Abnormal Conditions	**Abnormal Conditions**
Septic shock (early stages)	Septic shock (late stages)
Hyperthermia	Congestive heart failure
Hypervolemia	Hypovolemia
Decreased vascular resistance	Pulmonary emboli
	Increased vascular resistance
	Myocardial infarction
	Hyperinflation of Lungs
	Mechanical ventilation
	Continuous positive airway pressure (CPAP)
	Positive end-expiratory pressure (PEEP)

Clinical Connection 15-3

Cor Pulmonale—Hemodynamic Changes

Cor pulmonale is the enlargement of the *right* ventricle caused by primary lung disease. Cor pulmonale eventually results in the inability of the right ventricle to pump blood effectively to the lungs (also called right-heart failure). When the right ventricle starts to fail, blood returning to the heart backs up and pools throughout the peripheral vascular system—for example, in the liver, legs, neck veins, ankles, feet, and hands. Hemodynamic changes associated with cor pulmonale are shown in the accompanying table.

Hemodynamic Indices

CVP	RAP	$\overline{\text{PAP}}$	PCWP	CO	SV	SVI	CI	RVSWI	LVSWI	PVR	SVR
↑↑	↑↑	↓	↓	○	○	○	○	○	○	○	○

○ = unchanged

Stroke Volume Index

The stroke volume index (SVI) (also known as stroke index) is derived by dividing the stroke volume (SV) by the body surface area (BSA).

$$\text{SVI} = \frac{\text{SV}}{\text{BSA}}$$

For example, if a patient has a stroke volume of 60 mL and a body surface area of 2 m^2, the stroke volume index would be determined as follows:

$$\begin{aligned}\text{SVI} &= \frac{\text{SV}}{\text{BSA}}\\ &= \frac{60\ \text{mL/beat}}{2\ \text{m}^2}\\ &= 30\ \text{mL/beat/m}^2\end{aligned}$$

Assuming that the heart rate remains the same, as the stroke volume index increases or decreases, the cardiac index also increases or decreases.

Clinical Connection 15-4

Congestive Heart Failure—Hemodynamic Changes

Congestive heart failure (CHF) (also called left-heart failure) is the inability of the *left* ventricle to pump blood effectively. When a patient has CHF, the right ventricle continues to pump blood to the lungs, but the left ventricle does not adequately pump the returning blood from the lungs into the systemic circulation. As a result, the vascular system in the lungs becomes engorged with blood, the

(*Continued*)

Clinical Connection 15-4, Continued

pulmonary capillary blood pressure increases, and fluid leaks out of the capillaries into the alveoli—causing the condition known as **pulmonary edema**.

Hemodynamic changes associated with CHF are shown in the accompanying table.

Hemodynamic Indices

CVP	RAP	$\overline{PAP}$	PCWP	CO	SV	SVI	CI	RVSWI	LVSWI	PVR	SVR
○	↑	↑	↑↑	↓	↓	↓	↓	↑	↓	↑	↓

○ = unchanged

The stroke volume index reflects the (1) contractility of the heart, (2) overall blood volume status, and (3) amount of venous return. Table 15–3 lists factors that increase and decrease the stroke volume index.

Cardiac Index

The cardiac index (CI) is calculated by dividing the cardiac output (CO) by the body's surface area (BSA).

$$CI = \frac{CO}{BSA}$$

Clinical Connection 15-5

COPD—Hemodynamic Changes

Respiratory disorders classified as **chronic obstructive pulmonary disorders (COPD)** are chronic bronchitis, emphysema, cystic fibrosis, and bronchiectasis. Hemodynamic changes associated with COPD are shown in the accompanying table.

Hemodynamic Indices

CVP	RAP	$\overline{PAP}$	PCWP	CO	SV	SVI	CI	RVSWI	LVSWI	PVR	SVR
↑	↑	↑↑	○	○	○	○	○	↑	○	↑	○

○ = unchanged

For example, if a patient has a cardiac output of 5 L/min and a body surface area of 2 m^2, the cardiac index is computed as follows:

$$\begin{aligned} CI &= \frac{CO}{BSA} \\ &= \frac{5\ \text{L/min}}{2\ \text{m}^2} \\ &= 2.5\ \text{L/min/m}^2 \end{aligned}$$

See Table 15–3 for a list of factors that increase and decrease the cardiac index.

Right Ventricular Stroke Work Index

The right ventricular stroke work index (RVSWI) measures the amount of work required by the right ventricle to pump blood. The RVSWI is a reflection of the contractility of the right ventricle. In the presence of normal right ventricular contractility, increases in afterload (e.g., caused by pulmonary vascular constriction) cause the RVSWI to increase until a plateau is reached. When the contractility of the right ventricle is diminished by the presence of disease, the RVSWI does not increase appropriately. The RVSWI is derived from the following formula:

$$\text{RVSWI} = \text{SVI} \times (\overline{\text{PAP}} - \text{CVP}) \times 0.0136 \text{ g/mL}$$

where SVI is stroke volume index, $\overline{\text{PAP}}$ is mean pulmonary artery pressure, CVP is central venous pressure, and the density of mercury factor 0.0136 g/mL is needed to convert the equation to the proper units of measurement—that is, gram meters/square meter (g m/m^2).

For example, if a patient has an SVI of 35 mL, a $\overline{\text{PAP}}$ of 20 mm Hg, and a CVP of 5 mm Hg, the patient's RVSWI is calculated as follows:

$$\begin{aligned}\text{RVSWI} &= \text{SVI} \times (\overline{\text{PAP}} - \text{CVP}) \times 0.0136 \text{ g/mL} \\ &= 35 \text{ mL/beat/m}^2 \times (20 \text{ mm Hg} - 5 \text{ mm Hg}) \times 0.0136 \text{ g/mL} \\ &= 35 \text{ mL/beat/m}^2 \times 15 \text{ mm Hg} \times 0.0136 \text{ g/mL} \\ &= 7.14 \text{ g m/m}^2\end{aligned}$$

Factors that increase and decrease the RVSWI index are listed in Table 15–3.

Left Ventricular Stroke Work Index

The left ventricular stroke work index (LVSWI) measures the amount of work required by the left ventricle to pump blood. The LVSWI is a reflection of the contractility of the left ventricle. In the presence of normal left ventricular contractility, increases in afterload (e.g., caused by systemic vascular constriction) cause the LVSWI to increase until a plateau is reached. When the contractility of the left ventricle is diminished by the presence of disease, the LVSWI does not increase appropriately. The following formula is used for determining this hemodynamic variable:

$$\text{LVSWI} = \text{SVI} \times (\text{MAP} - \text{PCWP}) \times 0.0136 \text{ g/mL}$$

Clinical Connection 15-6

Lung Collapse—Hemodynamic Changes

Respiratory disorders that cause the lung to collapse include flail chest, pneumothorax, and hemothorax. Hemodynamic changes associated with lung collapse are shown in the accompanying table.

Hemodynamic Indices

CVP	RAP	$\overline{\text{PAP}}$	PCWP	CO	SV	SVI	CI	RVSWI	LVSWI	PVR	SVR
↑	↑	↑	↓	↓	↓	↓	↓	↑	↓	↑	↓

○ = unchanged

where SVI is stroke volume index, MAP is mean arterial pressure, PCWP is pulmonary capillary wedge pressure, and the density of mercury factor 0.0136 g/mL is needed to convert the equation to the proper units of measurement—that is, g m/m^2.

For example, if a patient has an SVI of 30 mL, an MAP of 100 mm Hg, and a PCWP of 5 mm Hg, then:

$$\begin{aligned}\text{LVSWI} &= \text{SVI} \times (\text{MAP} - \text{PCWP}) \times 0.0136\ \text{g/mL}\\ &= 30\ \text{mL/beat/m}^2 \times (100\ \text{mm Hg} - 5\ \text{mm Hg}) \times 0.0136\ \text{g/mL}\\ &= 30\ \text{mL/beat/m}^2 \times (95\ \text{mm Hg}) \times 0.0136\ \text{g/mL}\\ &= 38.76\ \text{g m/m}^2\end{aligned}$$

Table 15–3 lists factors that increase and decrease the LVSWI.

Clinical Connection 15-7

Hypovolemia—Hemodynamic Changes

Hypovolemia is a blood disorder consisting of a decrease in the volume of circulating blood. Common causes include dehydration, bleeding, vomiting, severe burns, and drugs such as diuretics or vasodilators used to treat hypertensive individuals. Hemodynamic changes associated with hypovolemia are shown in the accompanying table.

Hemodynamic Indices

CVP	RAP	$\overline{\text{PAP}}$	PCWP	CO	SV	SVI	CI	RVSWI	LVSWI	PVR	SVR
↓↓	↓	↓	↓	↓	↓	↓	↓	↓	↓	○	↑

○ = unchanged

Vascular Resistance

As blood flows through the pulmonary and the systemic vascular system, there is resistance to flow. The pulmonary system is a *low-resistance* system, whereas the systemic vascular system is a *high-resistance* system.

Pulmonary Vascular Resistance

The pulmonary vascular resistance (PVR) measurement reflects the afterload of the right ventricle. It is calculated by the following formula:

$$\text{PVR} = \frac{\overline{\text{PAP}} - \text{PCWP}}{\text{CO}} \times 80$$

where $\overline{\text{PAP}}$ is the mean pulmonary artery pressure, PCWP is the pulmonary capillary wedge pressure, CO is the cardiac output, and 80 is a conversion factor for adjusting to the correct units of measurement (dyne × sec × cm^{-5}).

TABLE 15-4 Factors That Increase Pulmonary Vascular Resistance (PVR)

Chemical Stimuli

- Decreased alveolar oxygenation (alveolar hypoxia)
- Decreased pH (acidemia)
- Increased P_{CO_2} (hypercapnia)

Pharmacologic Agents

- Epinephrine
- Norepinephrine
- Dobutamine
- Dopamine
- Phenylephrine

Hyperinflation of Lungs

- Mechanical ventilation
  - Continuous positive airway pressure (CPAP)
  - Positive end-expiratory pressure (PEEP)

Pathologic Factors

- Vascular blockage
  - Pulmonary emboli
  - Air bubble
  - Tumor mass

- Vascular wall disease
  - Sclerosis
  - Endarteritis
  - Polyarteritis
  - Scleroderma

- Vascular destruction
  - Emphysema
  - Pulmonary interstitial fibrosis

- Vascular compression
  - Pneumothorax
  - Hemothorax
  - Tumor

Humoral Substances

- Histamine
- Angiotensin
- Fibrinopeptides
- Prostaglandin $F_{2\alpha}$
- Serotonin

For example, to determine the PVR of a patient who has a $\overline{PAP}$ of 15 mm Hg, a PCWP of 5 mm Hg, and a CO of 5 L/min:

$$\begin{aligned} PVR &= \frac{\overline{PAP} - PCWP}{CO} \times 80 \\ &= \frac{15 \text{ mm Hg} - 5 \text{ mm Hg}}{5 \text{ L/min}} \times 80 \\ &= \frac{10 \text{ mm Hg}}{5 \text{L/min}} \times 80 \\ &= 160 \text{ dynes} \times \text{sec} \times \text{cm}^{-5} \end{aligned}$$

Table 15–4 lists factors that increase the pulmonary vascular resistance. Factors that decrease the pulmonary vascular resistance are listed in Table 15–5.

TABLE 15-5 Factors That Decrease Pulmonary Vascular Resistance (PVR)

Pharmacologic Agents	Humoral Substances
Oxygen	Acetylcholine
Isoproterenol	Bradykinin
Aminophylline	Prostaglandin E
Calcium-channel blocking agents	Prostacyclin (prostaglandin I_2)

Clinical Connection 15-8

Pulmonary Embolism—Hemodynamic Changes

A **pulmonary embolism** is the blockage of a pulmonary artery by fat, air tumor, or thrombus that usually arises from a peripheral vein (most frequently one of the deep veins of the legs). Hemodynamic changes associated with pulmonary embolism are shown in the accompanying table.

Hemodynamic Indices

CVP	RAP	$\overline{\text{PAP}}$	PCWP	CO	SV	SVI	CI	RVSWI	LVSWI	PVR	SVR
↑	↑	↑↑	↓	↓	↓	↓	↓	↑	↓	↑	○

○ = unchanged

Systemic or Peripheral Vascular Resistance

The systemic or peripheral vascular resistance (SVR) measurement reflects the afterload of the left ventricle. It is calculated by the following formula:

$$\text{SVR} = \frac{\text{MPA} - \text{CVP}}{\text{CO}} \times 80$$

where MAP is the mean arterial pressure, CVP is the central venous pressure, CO is the cardiac output, and 80 is a conversion factor for adjusting to the correct units of measurement (dyne × sec × cm^{-5}). (*Note:* The right atrial pressure [RAP] can be used in place of the CVP value.)

For example, if a patient has an MAP of 80 mm Hg, a CVP of 5 mm Hg, and a CO of 5 L/min, then:

$$\begin{aligned}\text{SVR} &= \frac{\text{MAP} - \text{CVP}}{\text{CO}} \times 80\\ &= \frac{80\text{ mm Hg} - 5\text{ mm Hg}}{5\text{ L/min}} \times 80\\ &= \frac{75\text{ mm Hg} \times 80}{5\text{ L/min}}\\ &= 1200\text{ dynes} \times \text{sec} \times \text{cm}^{-5}\end{aligned}$$

Table 15–6 lists factors that increase and decrease the systemic vascular resistance.

TABLE 15-6 Factors That Increase and Decrease Systemic Vascular Resistance (SVR)

Increases SVR	Decreases SVR
Vasoconstricting Agents Dopamine Norepinephrine Epinephrine Phenylephrine	**Vasodilating Agents** Nitroglycerin Nitroprusside Morphine Inamrinone Hydralazine Methyldopa Diazoxide Phentolamine
Abnormal Conditions Hypovolemia Septic shock (late stages) ↓P_{CO_2}	**Abnormal Conditions** Septic shock (early stages) ↑P_{CO_2}

↑ increased, ↓ decreased

Chapter Summary

The hemodynamic status of the critically ill patient can be directly measured at the bedside using a pulmonary catheter. Direct hemodynamic measurements include the central venous pressure (CVP), right atrial pressure (RAP), mean pulmonary artery pressure ($\overline{\text{PAP}}$), pulmonary capillary wedge pressure (PCWP), and cardiac output (CO). The direct hemodynamic measurements, in turn, can be used to compute the following hemodynamic values: stroke volume (SV), stroke volume index (SVI), cardiac index (CI), right ventricular stroke work index (RVSWI), left ventricular stroke work index (LVSWI), pulmonary vascular resistance (PVR), and systemic vascular resistance (SVR). Currently, these calculations are obtained either from a programmed calculator or by using the hemodynamic formula and a handheld calculator.

Clinical connections associated with the preceding topics include (1) a case study that illustrates the adverse effects of an elevated afterload on a patient's hemodynamic parameters, (2) a case study that illustrates the use of best PEEP in adjusting a patient's hemodynamic profile, (3) cor pulmonale—hemodynamic changes, (4) congestive heart failure—hemodynamic changes, (5) COPD—hemodynamic changes, (6) lung collapse—hemodynamic changes, (7) hypovolemia—hemodynamic changes, and (8) pulmonary embolism—hemodynamic changes.

1 Clinical Application Case

A 71-year-old woman reported sudden chest pain to her husband while working in her garden. Moments later she collapsed; her husband called 911 immediately. Upon arrival, the paramedics charted these vital signs: blood pressure—64/35 mm Hg, heart rate—32 beats/min, and respiratory rate—4 breaths/min and shallow. Cardiopulmonary resuscitation (CPR) was initiated, and the patient was transferred to the hospital. En route to the hospital, an intravenous line was inserted, and a bolus of epinephrine was administered.

In the emergency department, the patient's vital signs were blood pressure—78/50 mm Hg, heart rate—42 beats/min, and spontaneous respiratory rate—16 breaths/min. Dopamine was administered, and the heart rate increased to 60 beats/min. Despite the improved heart rate, however, the patient's blood pressure remained low, and her skin was cold and clammy. After administration of 3 L/min oxygen via nasal cannula, the patient's arterial blood gas values were pH—7.54, Pa_{CO_2}—25 mm Hg, HCO_3^-—22 mEq/L, and Pa_{O_2}—62 mm Hg.

Her electrocardiogram (ECG) showed a complete heart block.[5] The patient was immediately transferred to the coronary care unit (CCU). At the bedside, a transvenous cardiac pacing wire was placed under fluoroscopy, and the ventricles were paced at a rate of 80 beats/min. A pulmonary catheter was then inserted (see Figure 15–1), and a hemodynamic profile was obtained (see Hemodynamic Profile No. 1).

After evaluating the first hemodynamic profile, the physician made the diagnosis of cardiogenic shock and prescribed nitroprusside for the patient. One hour later, while on an inspired oxygen concentration (FI_{O_2}) of 0.5, the patient's arterial blood gas values were pH—7.43, Pa_{CO_2}—33 mm Hg, HCO_3^-—24 mEq/L, and Pa_{O_2}—108 mm Hg. Urine output was 35 mL/hr. The patient's skin was warm and dry, and respiratory rate 12 breaths/min. At this time, a second hemodynamic profile was obtained (see Hemodynamic Profile No. 2).

Discussion

This case illustrates the adverse "ripple" effects of an elevated afterload (Chapter 5) on a patient's hemodynamic parameters. The very high SVR and PCWP and low CI in Hemodynamic Profile No. 1 showed that the patient's afterload was elevated. Although dopamine is a good agent to increase the patient's CI (cardiac index), in larger doses it causes the SVR (systemic vascular resistance) to increase. Because the SVR was already high, nitroprusside (a vasodilator) was used to reduce the patient's afterload.

(*continued*)

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[5] The ventricles were contracting independently from the sinus atrial node rhythm (Figure 14–28).

Clinical Application Case 1 (continued)

Hemodynamic Profile

Parameter*	Profile No. 1	Profile No. 2
BP	88/54	91/55
HR	80 paced	80 paced
CVP	9	9
RAP	10	10
$\overline{\text{PAP}}$	18	16
PCWP	21	13
CI	1.1	1.8
SVR	2295	1670
Urine output (mL/hr)	0	35

*BP = blood pressure; HR = heart rate; CVP = central venous pressure; RAP = right atrial pressure; $\overline{\text{PAP}}$ = mean pulmonary artery pressure; PCWP = pulmonary capillary wedge pressure; CI = cardiac index; SVR = systemic vascular resistance. Normal ranges are given in Tables 15–1 and 15–2.

After the administration of the nitroprusside, the patient's blood pressure essentially remained the same in the second hemodynamic profile, while her PCWP, CI, SVR, and urine output all improved significantly. In short, as the patient's SVR decreased in response to the nitroprusside, the left ventricular afterload also decreased. This action, in turn, allowed blood to be more readily ejected from the left ventricle. A cardiac pacemaker was permanently implanted and the patient progressively improved. The patient was discharged after 7 days.

2 Clinical Application Case

A 35-year-old man was found unconscious, face down, in about 4 inches of water at a local beach. He had fallen asleep on the beach at low tide while intoxicated. His pulse was weak, and he was not breathing. Someone called 911, and the lifeguard started cardiopulmonary resuscitation (CPR). When the paramedics arrived, CPR was continued with an inspired oxygen concentration ($F_{I_{O_2}}$) of 1.0, and the patient was transferred to the local hospital.

In the emergency department, the patient was semiconscious. Although he demonstrated a spontaneous respiratory rate of 8 breaths/min, his breathing was labored and shallow. His pulse rate was 115 beats/min and blood pressure was 95/60 mm Hg. Chest X-ray showed a normal-size heart, but patches of alveolar infiltrates (white areas) were visible throughout both lung fields. The laboratory report showed that the patient's alcohol level was 0.53; complete blood cell (CBC) count was normal; and hemoglobin level was normal, at 15 g/dL (refer to Chapter 6). On an $F_{I_{O_2}}$ of 1.0, his arterial blood gas values were pH—7.27, Pa_{CO_2}—62 mm Hg, HCO_3^-—26 mEq/L, and Pa_{O_2}—38 mm Hg.

The patient was intubated and transferred to the intensive care unit. At the time of intubation, sand and seaweed were suctioned from the patient's trachea. A pulmonary artery catheter and arterial line were inserted (see Figure 15–1). The patient was placed on a mechanical ventilator with the following settings:

Clinical Application Case 2 (continued)

tidal volume—750 mL, respiration rate—12 breath/min, Fi_{O_2}—1.0, and positive end-expiratory pressure (PEEP)—5 cm H_2O. The patient's arterial blood gas values on these settings were pH—7.47, Pa_{CO_2}—28 mm Hg, HCO_3^-—22 mEq/L, Pa_{O_2}—57 mm Hg, and Sa_{O_2}—91 percent. At this time, a hemodynamic profile and arterial blood sample were obtained (see Hemodynamic Profile No. 1).

Hemodynamic Profile

Parameter*	Profile No. 1 PEEP 5 cm H_2O	Profile No. 2 PEEP 10 cm H_2O	Profile No. 3 PEEP 5 cm H_2O
BP	90/60	95/68	91/62
HR	107	105	98
CI	1.9	1.5	1.9
CO	3.83	3.1	3.82
SVI	36	31	37
SVR	1490	170	1493

*BP = blood pressure; HR = heart rate; CI = cardiac index; CO = cardiac output; SVI = stroke volume index; SVR = systemic vascular resistance.

After reviewing the clinical data in the first hemodynamic profile, the physician had the respiratory therapist decrease the patient's tidal volume to 650 mL to increase the patient's Pa_{CO_2}, which had been reduced too much by the first ventilator settings (the decreased Pa_{CO_2} was the cause of elevated pH). Because the patient's Pa_{O_2} was still very low on an Fi_{O_2} of 1.0, the PEEP was increased to 10 cm H_2O. A second arterial blood gas analysis showed the following values: pH—7.42, Pa_{CO_2}—36 mm Hg, HCO_3^-—23 mEq/L, Pa_{O_2}—61 mm Hg, and Sa_{O_2}—90 percent. A second hemodynamic profile was then obtained (see Hemodynamic Profile No. 2).

After reviewing the patient's second arterial blood gas analysis and second hemodynamic profile, the physician had the respiratory therapist decrease the PEEP back to 5 cm H_2O. Fifteen minutes later, a third arterial blood gas analysis showed a pH of 7.42, Pa_{CO_2}—36 mm Hg, HCO_3^-—23 mEq/L, Pa_{O_2}—59 mm Hg, and Sa_{O_2}—90 percent. A third hemodynamic profile was then obtained (see Hemodynamic Profile No. 3). Despite the fact that the patient's Pa_{O_2} was less than satisfactory at this time, the physician asked the respiratory therapist to maintain the preceding treatment parameters.

Discussion

This case illustrates that the best level of PEEP (commonly referred to as "best PEEP") was the PEEP level that produced the least depression of cardiac output and the maximum total oxygen delivery. Inspection of the three hemodynamic profiles shows that 5 cm H_2O was the most effective by these criteria.[6] Despite the fact that the patient's clinical course was stormy, he was eventually weaned from the ventilator 16 days after his admission. Although he did regain consciousness, he was amnesic. He was also diagnosed to have moderate to severe mental and neuromuscular disorders. He was transferred to the rehabilitation unit where, at the time of this writing, progress was reported as slow.

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[6] Chapter 6 shows how the patient's oxygen delivery for each level of PEEP can be calculated by using the total oxygen delivery (D_{O_2}) formula. It is strongly recommended that the reader calculate and compare the D_{O_2} when the patient was on 5 cm H_2O PEEP versus 10 cm H_2O PEEP. The D_{O_2} formula will show that even though the patient's Pa_{O_2} was less than desirable at 5 cm H_2O of PEEP, the cardiac output (and, therefore, the total oxygen delivery) was greater.

Review Questions

Directions: On the line next to the hemodynamic parameters in Column A, match the normal range from Column B. Items in Column B may be used once, more than once, or not at all.

COLUMN A *Hemodynamic Parameters*	**COLUMN B** *Normal Range*
1. _______ Mean pulmonary artery pressure	**a.** 4–8 L/min
2. _______ Pulmonary vascular resistance	**b.** 800–1500 dynes × sec × cm^{-5}
3. _______ Cardiac output	**c.** 60–130 mL
4. _______ Left ventricular stroke work index	**d.** 2–8 mm Hg
5. _______ Central venous pressure	**e.** 20–120 dynes × sec × cm^{-5}
6. _______ Stroke volume index	**f.** 9–18 mm Hg
7. _______ Pulmonary capillary wedge pressure	**g.** 30–65 mL/beat/m^2
8. _______ Systemic vascular resistance	**h.** 80 mm Hg
9. _______ Right atrial pressure	**i.** 2.5–4.2 L/min/m^2
10. _______ Cardiac index	**j.** 4–12 mm Hg
	k. 40–60 g m/m^2
	l. 7–12 g m/m^2

11. Which of the following increases an individual's cardiac output?

1. Epinephrine
2. Hypovolemia
3. Mechanical ventilation
4. Hyperthermia
   - A. 1 only
   - B. 2 only
   - C. 3 only
   - D. 1 and 4 only

12. Pulmonary vascular resistance increases in response to

1. Acidemia
2. Oxygen
3. Mechanical ventilation
4. Epinephrine
   - A. 2 only
   - B. 3 only
   - C. 1 and 3 only
   - D. 1, 3, and 4 only

13. An individual's systemic vascular resistance increases in response to

1. Morphine
2. Hypovolemia
3. Increased P_{CO_2}
4. Epinephrine
   - A. 1 only
   - B. 2 only
   - C. 3 only
   - D. 2 and 4 only

14. Which of the following decreases an individual's stroke volume index?

1. Dobutamine
2. Mechanical ventilation
3. Propranolol
4. Congestive heart failure
   - A. 2 only
   - B. 4 only
   - C. 1 and 3 only
   - D. 2, 3, and 4 only

15. An individual's pulmonary vascular resistance decreases in response to

1. Bradykinin
2. Emphysema
3. Norepinephrine
4. Hypercapnia

A. 1 only
B. 2 only
C. 3 and 4 only
D. 2 and 3 only

Clinical Application Questions

Case 1

1. Although dopamine is a good agent to increase the patient's CI, in larger doses it causes

____

____

2. Why was nitroprusside administered in this case?

____

____

3. Why did the patient's PCWP, CI, SVR, and urine output all improve after the administration of nitroprusside?

____

____

Case 2

1. Why was a PEEP of 5 cm H_2O the "best PEEP" in this case?

____

____

2. Using the total oxygen delivery formula (D_{O_2}) (discussed in Chapter 6), calculate and compare the D_{O_2} when the patient was receiving 5 cm H_2O PEEP compared with 10 cm H_2O PEEP.

____

____

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CHAPTER 16

Renal Failure and Its Effects on the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

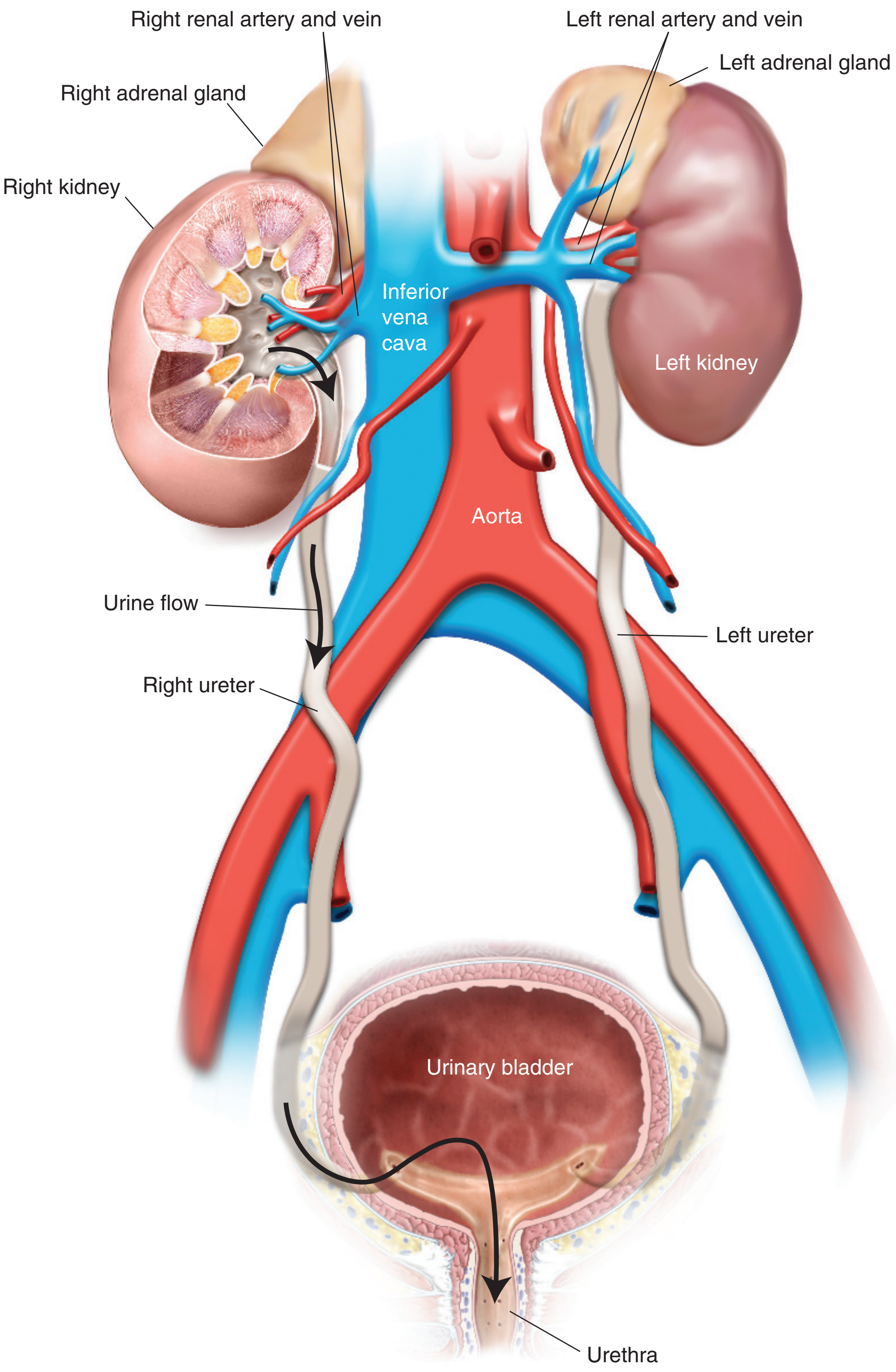
1. Describe how the following relate to the kidney: hilum, ureters, cortex, medulla, renal pelvis, major calyces, minor calyces, renal papillae, renal pyramid, and nephrons.
2. Describe how the following relate to the nephron: glomerulus, proximal tubule, loop of Henle, distal tubule, Bowman's capsule, renal corpuscle, proximal convoluted tubule, descending limb of the loop of Henle, ascending limb of the loop of Henle, distal convoluted tubule, and the collecting duct.
3. Explain how the blood vessels relate to the nephron.
4. Describe the formation of urine.
5. Explain the control of urine concentration and volume.
6. Describe the role of the kidneys in regulating sodium, potassium, calcium, magnesium, phosphate, and acid–base balance.
7. Describe the role of the capillary fluid shift system and the renal system in controlling the blood volume.
8. Identify common causes of renal disorders.
9. Describe how mechanical ventilation alters urinary output.
10. Describe cardiopulmonary problems that can develop with renal failure.

The composition of blood is largely determined by what the kidneys retain and excrete. The kidneys filter dissolved particles from the blood and selectively reabsorb the substances that are needed to maintain the normal composition of body fluids. When the renal system fails, a variety of indirect cardiopulmonary problems develop, including hypertension, congestive heart failure, pulmonary edema, anemia, and changes in acid–base balance. Because of this fact, a basic understanding of the cause, classification, and clinical manifestations of renal failure is essential in respiratory care.

The Kidneys

The kidneys are two bean-shaped organs located against the posterior wall of the abdominal cavity, one on each side of the vertebral column (Figure 16–1). In the adult, each kidney is about 12 cm long, 6 cm wide, and 3 cm thick. Medially, in the central concave portion of each kidney there is a longitudinal fissure called

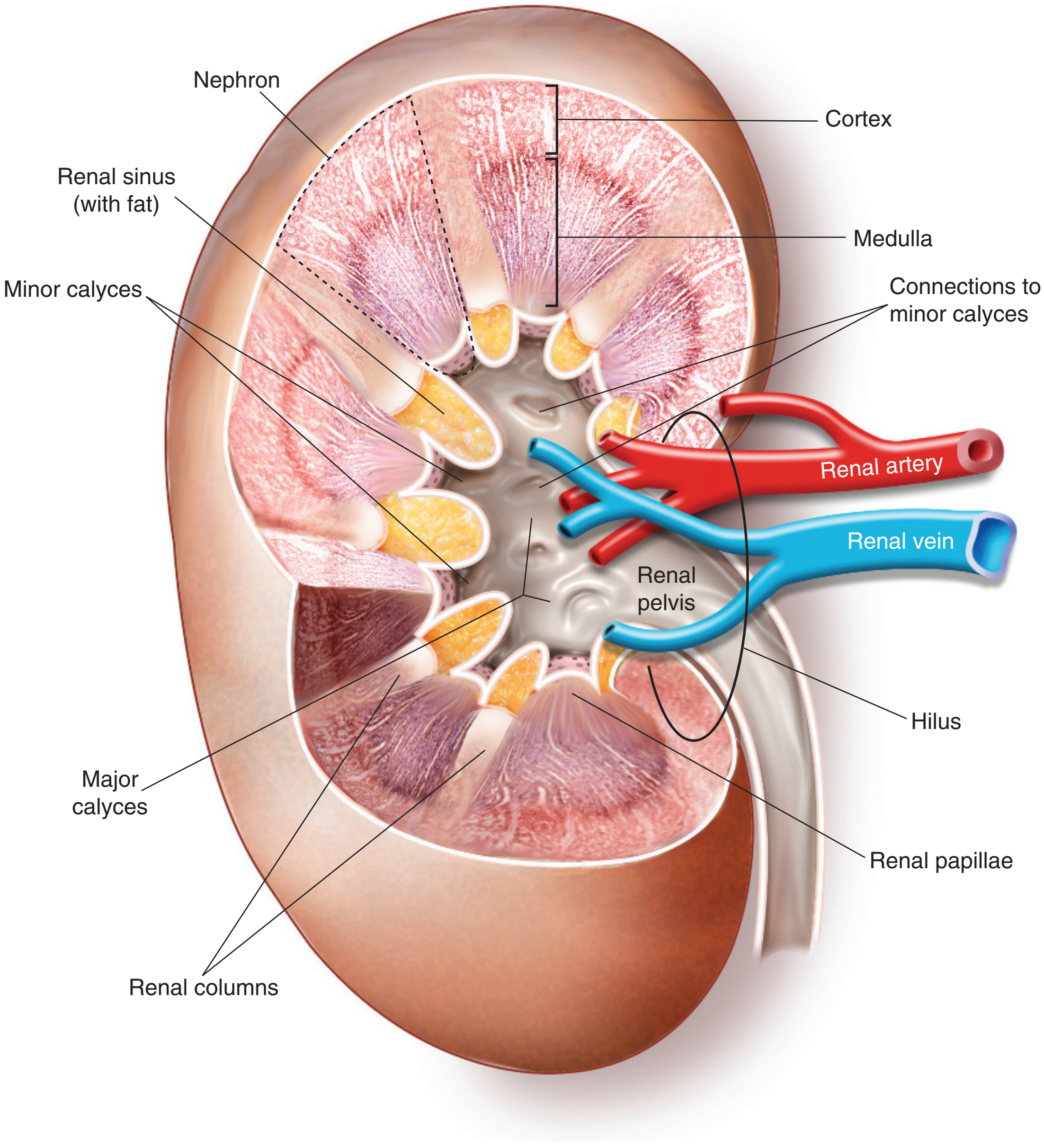
FIGURE 16-1 The organs of the urinary system. Urine is formed by the kidneys and flows through the ureters to the bladder, where it is eliminated via the urethra.


Right renal artery and vein
Left renal artery and vein
Left adrenal gland
Right adrenal gland
Right kidney
Inferior vena cava
Left kidney
Aorta
Urine flow
Left ureter
Right ureter
Urinary bladder
Urethra

the **hilum**. The renal artery, renal vein, and nerves enter and leave kidneys through the hilum. The **ureters**, which transport urine from the kidneys to the bladder, also exit the kidneys through the hilum.

As shown in Figure 16–2, the **cortex**, which is the outer one-third of the kidney, is a dark brownish red layer. The middle two-thirds of the kidney, the **medulla**, can be seen as a light-colored layer. Within the kidney, the ureter expands to form a funnel-shaped structure called the **renal pelvis**. The renal pelvis subdivides into two or three tubes called **major calyces** (singular, **calyx**), which in turn divide into several smaller tubes called **minor calyces**. A series of small structures called **renal papillae** (or *papillary ducts*) extends from the calyx toward the cortex of the kidney to form a triangular-shaped structure called the **renal pyramid**. The peripheral portions of the papillary ducts serve as collecting ducts for the waste products selectively filtered and excreted by the **nephrons**.

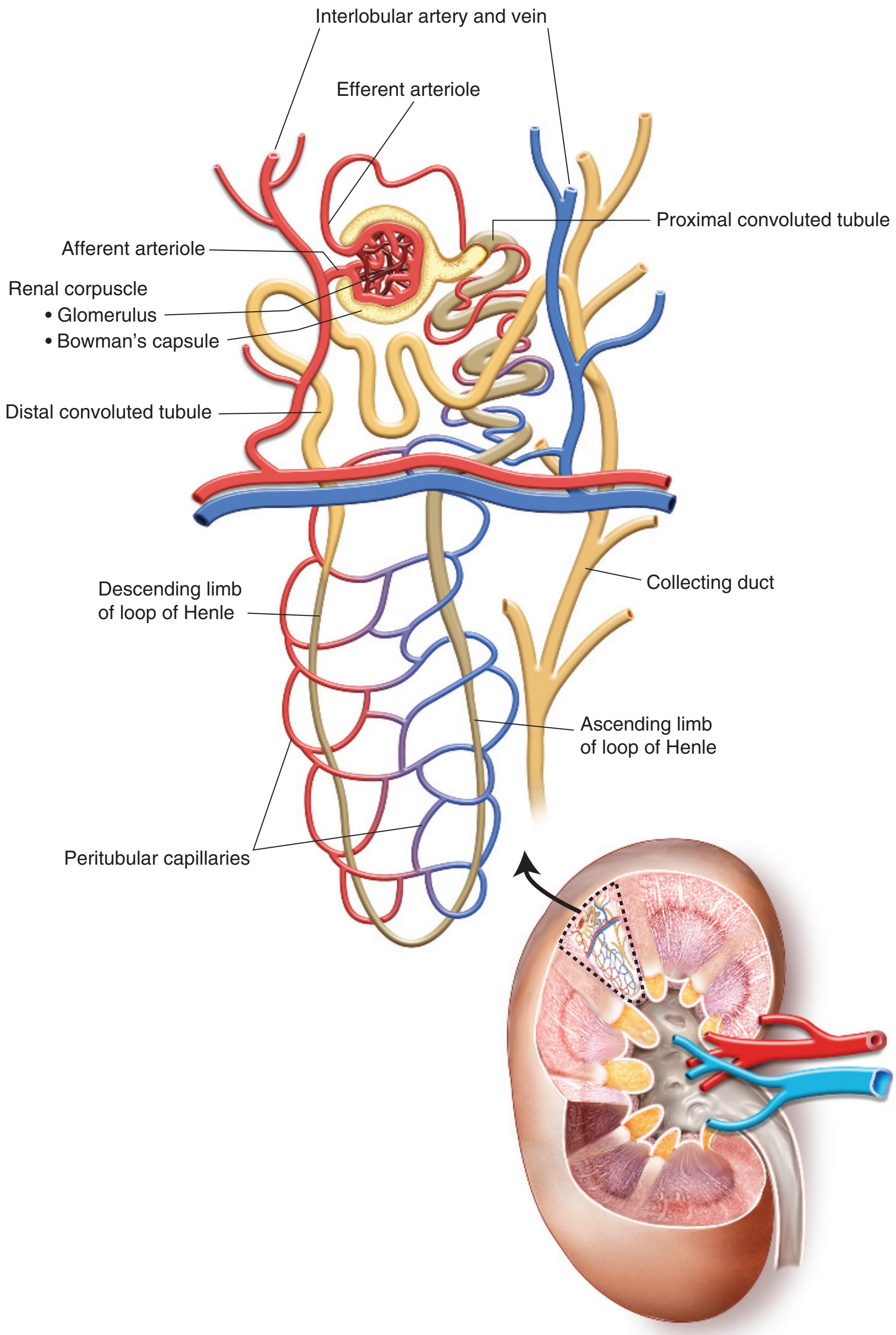
FIGURE 16–2 Cross-section of the kidney.


Nephron
Cortex
Renal sinus (with fat)
Medulla
Minor calyces
Connections to minor calyces
Renal artery
Renal vein
Renal pelvis
Hilus
Major calyces
Renal papillae
Renal columns

The Nephrons

The nephrons are the functional units of the kidneys (Figure 16–3). Each kidney contains about 1 million nephrons. Each nephron consists of a **glomerulus**, **proximal tubule**, **loop of Henle**, and **distal tubule**. The distal tubules empty into the collecting ducts. Although the collecting ducts technically are not part of the

FIGURE 16–3 The nephron.


Interlobular artery and vein
Efferent arteriole
Proximal convoluted tubule
Afferent arteriole
Renal corpuscle
• Glomerulus
• Bowman's capsule
Distal convoluted tubule
Collecting duct
Descending limb
of loop of Henle
Ascending limb
of loop of Henle
Peritubular capillaries

renal pyramid, they are considered a functional part of the nephron because of their role in urine concentration, ion salvaging, and acid–base balance.

The glomerulus consists of a network of interconnected capillaries encased in a thin-walled, saclike structure called **Bowman's capsule**. The glomerulus and Bowman's capsule constitute what is known as a **renal corpuscle**. Urine formation begins with the filtration of fluid and low-molecular-weight particles from the glomerular capillaries into Bowman's capsule. The substances that are filtered pass into the **proximal convoluted tubule**, which lies in the cortex.

The proximal tubule dips into the medulla to form the *descending* limb of the loop of Henle. The tubule then bends into a U-shaped structure to form the loop of Henle. As the tubule straightens, it ascends back toward the cortex as the *ascending* limb of the loop of Henle. The tubule again becomes convoluted as it enters the cortex. This portion of the nephron is called the **distal convoluted tubule** (see Figure 16–3). The distal convoluted tubule empties into the **collecting duct**. The collecting duct then passes through the renal pyramid to empty into the minor and major calyces, which in turn drain into the renal pelvis (see Figure 16–2). From the renal pelvis, the mixture of waste products (collectively referred to as urine) drains into the ureter, where it is carried by peristalsis to the urinary bladder. The urine is stored in the urinary bladder until it is discharged from the body through the urethra (see Figure 16–3).

Blood Vessels of the Kidneys

As shown in Figure 16–4, the right and left **renal arteries** carry blood to the kidneys. Shortly after passing through the hilum of the kidney, the renal artery divides into several branches called the **interlobar arteries**. At the base of the renal pyramids, the interlobar arteries become the **arcuate arteries**. Divisions of the arcuate arteries form a series of **interlobular arteries**, which enter the cortex and branch into the **afferent arterioles**.

The afferent arterioles deliver blood to the capillary cluster that forms the glomerulus. After passing through the glomerulus, the blood leaves by way of the efferent arterioles. The efferent arterioles then branch into a complex network of capillaries called the **peritubular capillaries**, which surround the various portions of the renal tubules of the nephron (see Figure 16–3).

The peritubular capillaries reunite to form the **interlobular veins**, followed by the **arcuate vein**, the **interlobar vein**, and the **renal vein**. The renal vein eventually joins the inferior vena cava as it courses through the abdominal cavity.

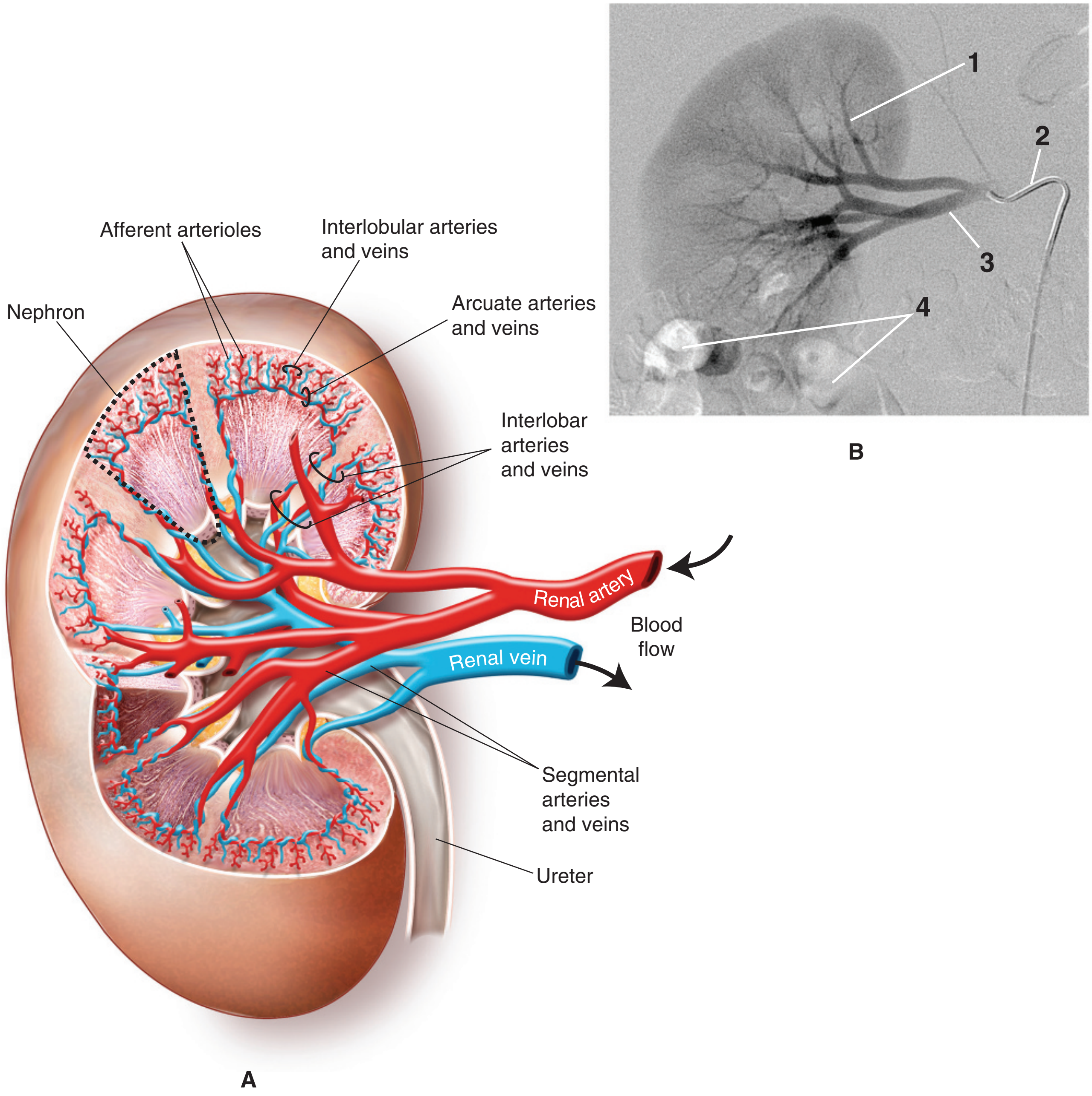
Urine Formation

The formation of urine involves glomerular filtration, tubular reabsorption, and tubular secretion.

Glomerular Filtration

Urine formation begins in the renal corpuscle. Water and dissolved substances such as electrolytes are forced out of the glomerular capillaries by means of the blood pressure *(hydrostatic pressure)*. The filtration of substances through the capillary membrane of the glomerulus is similar to the filtration in other capillaries throughout the body. The permeability of the glomerular capillary, however, is much greater than that of the capillaries in other tissues. As the filtrate leaves the glomerular capillaries, it is received in Bowman's capsule.

FIGURE 16-4 **A.** Illustration of the blood vessels of the kidney. **B.** Renal arteriogram: 1—interlobar artery; 2—tip of catheter in renal artery; 3—renal artery; 4—intestine. It is not unusual to have portions of the intestine overlying the kidney on renal arteriogram studies.


1
2
3
4
B
Afferent arterioles
Interlobular arteries and veins
Nephron
Arcuate arteries and veins
Interlobar arteries and veins
Renal artery
Blood flow
Renal vein
Segmental arteries and veins
Ureter
A

The rate of filtration is directly proportional to the hydrostatic pressure of the blood. The hydrostatic pressure in the glomerular capillary is about 55 mm Hg. This pressure, however, is partially offset by the hydrostatic pressure in Bowman's capsule of about 15 mm Hg. The osmotic pressure of the plasma is another important factor that offsets glomerular filtration. In other words, in the capillaries, the hydrostatic pressure acting to move water and dissolved particles outward is opposed by the inward osmotic pressure generated by the presence of protein in the plasma. Under normal conditions, the osmotic pressure is about 30 mm Hg. As shown in Table 16–1, the net filtration pressure, which is the algebraic sum of the

TABLE 16-1 Forces of Glomerular Filtration

Factors	Force
Enhances Filtration	
Glomerular capillary blood pressure	+55 mm Hg
Opposes Filtration	
Fluid pressure in Bowman's capsule	−15 mm Hg
Osmotic force (caused by the protein concentration difference)	−30 mm Hg
Net Filtration Pressure	+10 mm Hg

three relevant forces, is about 10 mm Hg. The glomeruli filter about 125 mL of fluid per minute (about 180 L/day). Of this 125 mL, however, only about 1 mL is excreted as urine. The average urine output is about 60 mL/hour, or 1440 mL/day.

Tubular Reabsorption

As the glomerular filtrate passes through the (1) proximal convoluted tubule, (2) loop of Henle, and (3) distal convoluted tubule, water, sodium, glucose, and other substances leave the tubule and enter the blood in the peritubular capillaries. Some substances, such as glucose and amino acids, are completely reabsorbed. About 99 percent of the filtered water and sodium is reabsorbed. About 50 percent of urea is reabsorbed and the electrolyte reabsorption is generally a function of need.

Although tubular reabsorption occurs throughout the entire renal tubule system, the bulk of it occurs in the proximal convoluted portion. Certain sections of the tubule, however, reabsorb specific substances, using particular modes of transport. For example, the proximal tubule reabsorbs glucose by means of *active transport,* whereas water reabsorption occurs throughout the renal tubule by *osmosis.*

Tubular Secretion

Tubular secretion is the mechanism by which various substances are transported from the plasma of the peritubular capillaries to the fluid of the renal tubule (the *opposite* direction of tubular reabsorption). In essence, this mechanism constitutes a second pathway through which fluid can gain entrance into the renal tubule (the first being *glomerular filtration*). The most important substances transported into the tubules by means of secretion are hydrogen (H^+) and potassium (K^+) ions. In fact, most of the hydrogen and potassium ions found in the urine enter the tubules by secretion. Thus, the mechanisms that control the rates of tubular hydrogen and potassium secretion regulate the level of these substances in the blood.

Urine Concentration and Volume

The composition and volume of extracellular fluids are controlled by the kidneys' ability to produce either a dilute or concentrated urine. The kidneys are able to do this by two mechanisms: the **countercurrent mechanism** and the **selective permeability of the collecting ducts**.

Countercurrent Mechanism

The countercurrent mechanism controls water reabsorption in the distal tubules and collecting ducts. It accomplishes this through the unique anatomic position of certain nephrons. About one in every five nephrons descends deep into the renal medulla. These nephrons are called **juxtamedullary nephrons**. The normal osmolality of the glomerular filtrate is approximately 300 mOsm/L.[1] The osmolality of the interstitial fluid increases from about 300 mOsm/L in the cortex to about 1200 mOsm/L as the juxtamedullary nephron descends into the renal medulla. This sets up a strong active transport of sodium out of the descending limb of the loop of Henle. The increased amount of sodium in the interstitial fluid, in turn, prevents water from returning to the peritubular capillaries surrounding the tubules.

Selective Permeability

As shown in Figure 16–5, the permeability of the collecting ducts is regulated by the antidiuretic hormone (ADH), which is produced in the hypothalamus and is released by the pituitary gland. The hypothalamic cells manufacture ADH in response to input from numerous vascular baroreceptors, particularly a group found in the left atrium (see Figure 16–5). When the atrial blood volume and, therefore, pressure increase, the baroreceptors are activated to transmit neural impulses to the hypothalamus, causing the production of ADH to be inhibited. This causes tubules to be impermeable to water and the urine to be greater in volume and more dilute.

In contrast, decreased atrial pressure *(dehydration)* decreases the neural impulses originating from the baroreceptors and causes the production of ADH to increase. The result is the rapid movement of water out of these portions of the tubules of the nephron and into the interstitium of the medullary area by osmosis. This causes the urine volume to decrease and its concentration to increase.

The specific gravity *(osmolality)* of urine varies with its concentration of solutes. The urine produced by the healthy kidney has a specific gravity of about 1.003 to 1.030 under normal conditions. During periods of diminished renal function, the urine–specific gravity may fall to levels of 1.008 to 1.012.

Regulation of Electrolyte Concentration

The kidneys play a major role in maintaining a normal cellular environment by regulating the concentration of various ions. Some of the more important ions regulated by the kidneys are sodium, potassium, calcium, magnesium, and phosphate.

Sodium Ions

Sodium ions (Na^+) account for more than 90 percent of the positively charged ions in the extracellular fluid. Because the sodium ions cause almost all of the osmotic pressure of the fluids, it follows that the sodium ion concentration directly affects the osmolality of the fluids. Thus, when the sodium concentration increases, there is a corresponding increase in the extracellular fluid osmolality. In contrast, the extracellular fluid osmolality decreases when there is a decreased sodium concentration.

The kidneys control the concentration of sodium primarily by regulating the amount of water in the body. When the sodium level becomes too high, the amount of water in the body increases by (1) secretion of ADH, which causes the kidney to retain water, and (2) stimulation of thirst, which causes the individual to drink liquids.

Potassium Ions

A balanced potassium (K^+) level is essential for normal nerve and muscle function. When the potassium level becomes too low, muscle weakness, diarrhea, metabolic alkalosis, and cardiac arrhythmias develop—such as premature atrial and ventricular contractions, atrial and ventricular tachycardia, and ventricular fibrillation.

An excessively high potassium concentration causes muscle weakness, metabolic acidosis, and life-threatening arrhythmias (e.g., widening of the QRS complex). In response to a high K^+ level, the kidneys

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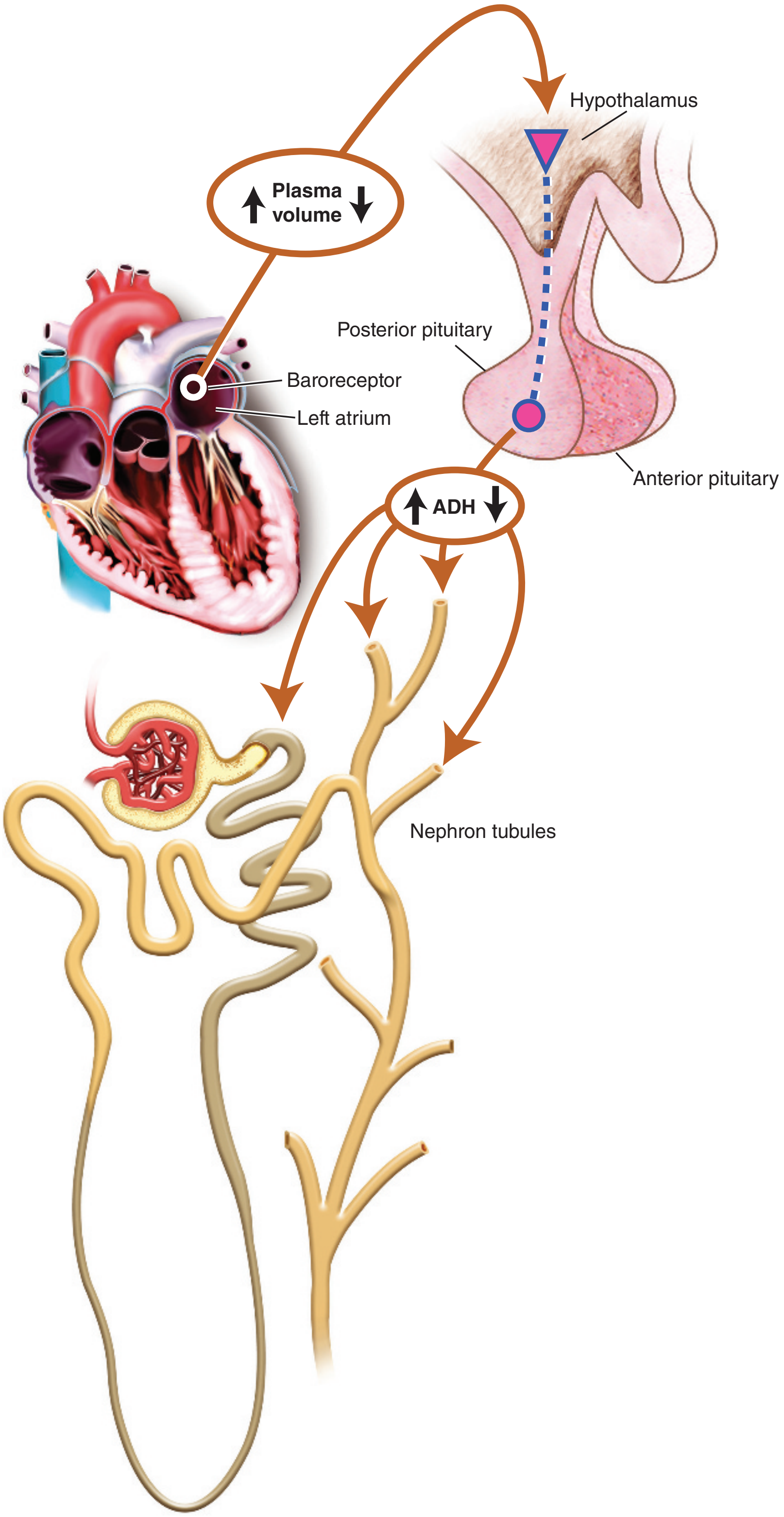
[1] Milliosmols (mOsm/L): 1000 milliosmols = 1 osmol, which is the unit in which osmotic pressure is expressed. We speak of osmols or milliosmols per liter.

FIGURE 16-5 The pathway by which antidiuretic hormone (ADH) is controlled. When the baroreceptors in the left atrium sense an increased pressure (increased plasma volume), they send neural impulses to the hypothalamus, causing the production of ADH to decrease. In contrast, a decreased pressure (decreased plasma volume) causes the production of ADH to increase.


Hypothalamus
↑ Plasma volume ↓
Posterior pituitary
Baroreceptor
Left atrium
Anterior pituitary
↑ ADH ↓
Nephron tubules

work to return the concentration to normal by means of two negative feedback control mechanisms: (1) the direct effect the excess potassium has on the epithelial cells of the renal tubules to cause an increased transport of potassium out of the peritubular capillaries and into the tubules of the nephrons, where it is subsequently passed in the urine, and (2) the stimulating effect the elevated potassium level has on the adrenal cortex, causing it to release increased quantities of *aldosterone*. Aldosterone stimulates the tubular epithelial cells to transport potassium ions into the nephron tubules and, hence, into the urine. The extracellular potassium concentration is normally 3.5 to 5 mEq/L.

Calcium, Magnesium, and Phosphate Ions

The precise mechanisms by which calcium, magnesium, and phosphate concentrations are regulated by the kidneys are not well understood. It is known, however, that elevated levels of any one of these ions in the extracellular fluid cause the tubules to decrease reabsorption and to pass the substances into the urine. In contrast, when any one of these substances is low in concentration, the tubules rapidly reabsorb the substance until its concentration in the extracellular fluids returns to normal.

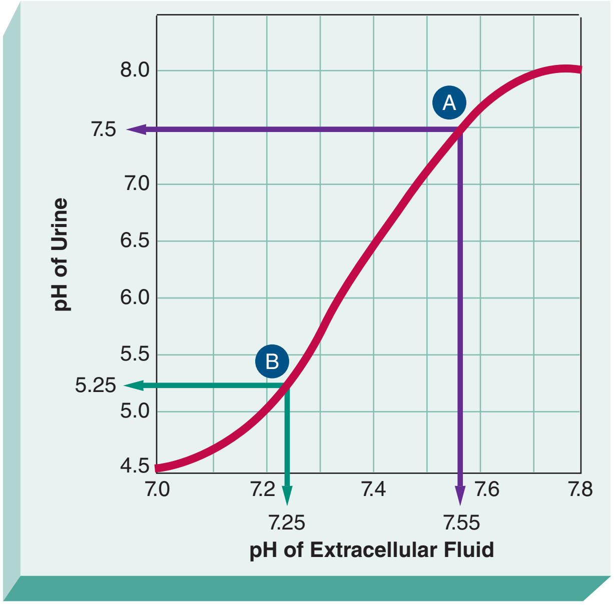
Role of the Kidneys in Acid–Base Balance

In addition to the natural acid–base buffers (refer to Chapter 7) of the body fluids (e.g., HCO_3^-, phosphate, and protein buffers), and the respiratory system's ability to regulate the elimination of CO_2, the renal system also plays an important role in maintaining a normal acid–base balance by its ability to regulate the excretion of hydrogen ions and the reabsorption of bicarbonate ions.

All renal tubules are capable of secreting hydrogen ions. The rate of secretion is directly proportional to the hydrogen ion concentration in the blood. Thus, when the extracellular fluids become too acidic, the kidneys excrete hydrogen ions into the urine. In contrast, when the extracellular fluids become too alkaline, the kidneys excrete basic substances (primarily sodium bicarbonate) into the urine.

This principle is illustrated in Figure 16–6, which shows that at point A, the pH of the extracellular fluid is 7.55. Because this is alkaline, the pH of the urine is also alkaline (pH 7.5) as the kidneys excrete alkaline

FIGURE 16–6 The effect of extracellular fluid pH on urine pH.



substances from the body fluids. In contrast, the extracellular pH at point B is 7.25 and the pH of the urine is very acidic (pH 5.25) because of excretion of large quantities of acidic substances (primarily hydrogen ions) from the body fluids. In both of these examples, the excretion of either acidic or alkaline substances moves the pH toward normal.

Blood Volume

In the adult, the normal blood volume is about 5 L, and it rarely increases or decreases more than a few hundred milliliters from that value. The capillary fluid shifts and the renal system are the two major mechanisms responsible for this constancy of the blood volume.

Capillary Fluid Shift System

Under normal circumstances, the pressure in the systemic capillaries is about 17 mm Hg. When the pressure rises above this value, fluid begins to leak into the tissue spaces, causing the blood volume to decrease toward normal. In contrast, when the blood volume falls, the capillary pressure decreases, and fluid is then absorbed from the interstitial spaces, causing the blood volume to move back toward normal. This mechanism, however, has its limitations because the tissue spaces cannot expand indefinitely when the blood volume becomes too high, nor can the tissue spaces supply an inexhaustible amount of fluid when the blood volume is too low.

Renal System

When the blood volume increases, the glomerular pressure in the kidney rises, causing the amount of the glomerular filtrate and the volume of the urine to increase. In addition, the pressure in the peritubular capillaries decreases fluid reabsorption from the tubules, which further increases the volume of urine.

Increased blood volume increases the glomerular pressure (normally 60 mm Hg) by means of two mechanisms: (1) the increased blood volume increases the blood flow through the afferent arterioles that lead into the kidneys and thus increases the intrarenal pressure, and (2) the increased blood volume stretches the atria of the heart, which contain stretch receptors called **volume receptors**. When the volume receptors in the atria are stretched, a neural reflex is initiated, which causes the renal afferent arterioles to dilate. This causes the blood flow into the kidneys to increase and thus increases the amount of urine formed. Furthermore, when the volume receptors are stretched, the secretion of ADH by the posterior pituitary gland is inhibited, which in turn increases the urine output.

Clinical Connection 16-1

Case Study—Adverse Effects of Poor Blood Circulation on Kidney and Lung Function

In the Clinical Application Case 1 (page 514), the respiratory therapist is called to help care for a 73-year-old woman who was admitted to the hospital for severe renal failure and left ventricular heart failure. This case illustrates how poor blood circulation adversely affects the patient's lung and kidney functions. The case further shows how all the clinical manifestations demonstrated in this case—for example, white fluffy patches on the chest X-ray and a shape reduction in urine output—can be traced back to the patient's left ventricular failure (a prerenal abnormality).

Renal Failure

The renal system is subject to the same types of disorders as other organs. The more common causes of renal failure are (1) congenital disorders, (2) infections, (3) obstructive disorders, (4) inflammation and immune responses, and (5) neoplasms.

Common Causes of Renal Disorders

Congenital Disorders

Approximately 10 percent of infants are born with a potentially life-threatening malformation of the renal system. Such abnormalities include unilateral renal agenesis, renal dysplasia, and polycystic disease of the kidney.

Infections

Urinary tract infections are the second most common type of bacterial infections (after respiratory tract infections). Urinary tract infections are seen more often in women than men. Approximately 20 percent of all women will develop at least one urinary tract infection during their lifetime. These infections range from bacteriuria to severe kidney infections that cause irreversible damage to the kidneys.

Obstructive Disorders

Urinary obstruction can affect all age groups and can occur in any part of the urinary tract. About 90 percent of obstructions are located below the level of the glomerulus. Some factors that predispose individuals to urinary flow obstruction are listed in Table 16–2. Persons who have a urinary obstruction are prone to infections, a heightened susceptibility to calculus formation, and permanent kidney damage.

Inflammation and Immune Responses

Kidney inflammation is caused by altered immune responses, drugs and related chemicals, and radiation. Inflammation can cause significant alterations in the glomeruli, tubules, and interstitium. The various forms of glomerulonephritis are believed to be caused by natural immune responses.

Neoplasms

Cancer of the kidneys accounts for 1 to 2 percent of all cancers. Although cancer of the kidneys is relatively rare in the adult, one form of cancer—Wilms' tumor—accounts for about 70 percent of all cancers of early childhood.

Classification of Renal Disorders

Renal disorders are commonly classified according to the anatomic portion of the renal system responsible for the renal decline. The major classifications are (1) prerenal, (2) renal, and (3) postrenal.

TABLE 16-2 Factors That Obstruct Urinary Flow

Calculi (bladder or kidney stones)
Normal pregnancy
Prostatic hypertrophy
Infection and inflammation causing scar tissue
Neurologic disorders (e.g., spinal cord injury, diabetic neuropathy)

Prerenal Conditions

Prerenal conditions consist of abnormalities that impair blood flow to the kidneys. Prerenal problems are the most common and generally are reversible if identified and treated early. Table 16–3 lists some common prerenal causes of renal failure.

Normally, about 20 to 25 percent of the cardiac output is filtered by the kidneys. When the volume of blood falls (e.g., in cardiac failure or hemorrhage), the blood flow to the kidneys may decrease sharply. Thus, one of the early clinical manifestations of prerenal failure is a sharp reduction in urine output.

Renal Conditions

Renal abnormalities involve conditions that obstruct flow through the kidneys. Table 16–4 lists the five categories of renal abnormalities.

Postrenal Conditions

An obstruction of the urinary tract at any point between the calyces and the urinary meatus is known as a postrenal obstruction. Table 16–5 lists some abnormalities included in the postrenal category.

TABLE 16-3 Prerenal Abnormalities

- Hypovolemia
  - Decrease of gastrointestinal tract fluid
  - Hemorrhage
  - Fluid sequestration (e.g., burns)
- Septicemia
- Heart failure
- Renal artery atherosclerosis

TABLE 16-4 Renal Abnormalities

- Renal ischemia
- Injury to the glomerular membrane caused by nephrotoxic agents
  - Aminoglycoside agents (e.g., gentamicin, kanamycin)
  - Heavy metals (e.g., lead, mercury)
  - Organic solvents (e.g., ethylene glycol)
  - Radiopaque contrast media
  - Sulfonamides
- Acute tubular necrosis
- Intratubular obstruction
  - Uric acid crystals
  - Hemolytic reactions (e.g., blood transfusion reactions)
- Acute inflammatory conditions
  - Acute pyelonephritis
  - Necrotizing papillitis

TABLE 16-5 Postrenal Abnormalities

- Ureteral obstruction (e.g., calculi, tumors)
- Bladder outlet obstruction (e.g., prostatic hypertrophy)

Clinical Connection 16-2

Case Study—A Prerenal Abnormality Caused by Second- and Third-Degree Burns

In the Clinical Application Case 2 (page 515), the respiratory therapist is called to help care for a 42-year-old male firefighter who was found unconscious in a smoke-filled room with second- and third-degree burns over portions of his left shoulder, left arm, and left hand and over the anterior portion of his chest and abdominal region. This case illustrates how the patient's burns caused fluid sequestration, which in turn caused hypovolemia—a prerenal abnormality.

Mechanical Ventilation as a Cause of Renal Failure

It is well documented that mechanical ventilation can alter urinary output. *Positive pressure ventilation* decreases urinary output, whereas *negative pressure ventilation* increases urinary output. It is believed that this is due in part to the blood pressure changes that occur in response to mechanical ventilation. In positive pressure ventilation, the venous return is often impeded, causing the blood volume and, therefore, the pressure in the atria to diminish. The reduced pressure stimulates the volume receptors in the atria to send more impulses to the pituitary gland, causing more ADH to be released. As the concentration of ADH increases, the amount of urine formed by the kidneys decreases.

Cardiopulmonary Disorders Caused by Renal Failure

In chronic renal failure, a variety of cardiopulmonary problems can develop. In acute renal failure, the body's ability to eliminate nitrogenous wastes, water, and electrolytes is impaired. As the renal system declines further, the blood urea nitrogen (BUN), creatinine, potassium, and phosphate levels rapidly increase, and metabolic acidosis develops. Water retention gives rise to peripheral edema and pulmonary congestion. During end-stage renal failure, virtually every portion of the body is affected. In terms of specific cardiopulmonary problems, the following problems can be expected in patients with renal failure.

Hypertension and Edema

When the renal function is impaired, the kidneys lose their ability to excrete sodium. Consequently, the ingestion of sodium leads to hypertension and edema.

Metabolic Acidosis

With the decline in renal function, the kidneys' ability to secrete hydrogen ions (H^+) and to conserve bicarbonate (HCO_3^-) progressively decreases. Furthermore, during the more advanced stages of renal failure, hyperkalemia is a frequent finding. Thus, because of the increased H^+ and K^+ ion levels and the loss of HCO_3^-, *metabolic acidosis* is an almost inevitable clinical manifestation in an end–stage renal failure (refer to Metabolic Acidosis in Chapter 7, page 330).

Renal Acid–Base Disturbances Caused by Electrolyte Abnormalities

Chloride abnormalities can lead to acid–base disturbances through the renal system. For example, when the plasma chloride (Cl^-) level falls below normal, the amount of Cl^- available for glomerular filtration decreases. Under normal circumstances, when the positive sodium ion (Na^+) is reabsorbed by the tubules, the negative Cl^- ion must also be reabsorbed to maintain electrical neutrality. In the absence of adequate amounts of Cl^-, however, the electrical balance is maintained by the secretion of hydrogen ions (H^+). The loss of H^+ results in *hypochloremic alkalosis.* In contrast, when the plasma Cl^- level is higher than normal, the secretion of H^+ ions is reduced. This, in turn, causes a reduction in bicarbonate reabsorption and *hyperchloremic acidosis.*

Potassium abnormalities can also lead to acid–base disturbances through the renal system. For example, under normal conditions, the potassium ion (K^+) behaves similarly to the H^+ ion in that it is secreted in the renal tubules in exchange for Na^+. In the absence of Na^+, neither K^+ nor H^+ can be secreted. When the K^+ level is higher than normal, however, the competition with H^+ for Na^+ exchange increases. When this happens, the amount of H^+ ions secreted is reduced, which in turn decreases the amount of HCO_3^- reabsorption. The end-product of this process is *hyperkalemic acidosis.* When the K^+ level is lower than normal, the competition with H^+ for Na^+ exchange decreases. Consequently, the amount of H^+ secreted is increased, which in turn increases the amount of HCO_3^- reabsorption. The end-product of this process is *hypokalemic alkalosis.*

Anemia

The kidneys are a primary source of the hormone *erythropoietin,* which stimulates the bone marrow to produce red blood cells (RBCs). When the renal system fails, the production of erythropoietin is often inadequate to stimulate the bone marrow to produce a sufficient number of RBCs. In addition, the toxic wastes that accumulate as a result of renal failure also suppress the ability of bone marrow to produce RBCs. Both of these mechanisms contribute to the anemia seen in chronic renal failure.

Bleeding

Approximately 20 percent of persons with chronic renal failure have a tendency to bleed as a result of platelet abnormalities. Clinically, this is manifested by epistaxis (nosebleed), gastrointestinal bleeding, and bruising of the skin and subcutaneous tissues.

Cardiovascular Problems

Hypertension is often an early sign of renal failure. In severe cases, the increased extracellular fluid volume, caused by sodium and water retention, gives rise to edema, congestive heart failure, and pulmonary edema. Pericarditis is also seen in about 50 percent of persons with chronic renal failure. This condition develops as a result of the pericardium being exposed to the metabolic end-products associated with renal decline.

Chapter Summary

When the renal system fails, a number of indirect cardiopulmonary problems can develop, such as hypertension, congestive heart failure, pulmonary edema, anemia, and changes in acid–base balance. Because of this fact, a basic understanding of the cause, classification, and clinical manifestations of renal failure is essential to advanced respiratory care. The primary content areas are the kidneys, including the hilum, ureters, cortex, medulla, renal pelvis, major calyces, renal papillae, and renal pyramid; the nephrons, including the glomerulus, proximal tubule, loop of Henle, distal tubule, Bowman's capsule, renal corpuscle, proximal convoluted tubule, distal convoluted tubule, and collecting duct; and the blood vessels of the kidneys, including the renal arteries, interlobar arteries, arcuate arteries, interlobular arteries, afferent and efferent arterioles, peritubular capillaries, interlobular veins, arcuate vein, interlobar vein, and renal vein.

In addition, the respiratory therapist needs a strong knowledge base of urine formation, including glomerular filtration, tubular reabsorption, and tubular secretion; urine concentration and volume, including countercurrent mechanism and selective permeability of the collecting ducts; the regulation of electrolyte concentration, including sodium, potassium, calcium, magnesium, and phosphate ions; and the role of the kidneys in acid–base balance and blood volume, including the capillary fluid shift system and the renal system. Causes of renal failure include congenital disorders, infections, obstructive disorders, inflammation and immune responses, neoplasms (tumors), and mechanical ventilation. Finally, chronic renal failure may lead to a variety of cardiopulmonary problems, including hypertension and edema, metabolic acidosis, electrolyte abnormalities, anemia, bleeding, and cardiovascular disorders.

Clinical connections associated with these topics include (1) the adverse effects of poor blood circulation on kidney and lung function and (2) a prerenal abnormality caused by second- and third-degree burns.

1 Clinical Application Case

A 73-year-old woman was admitted to the hospital for severe renal failure and left ventricular heart failure. An electrocardiogram (ECG) revealed a slow, irregular sinus rhythm with occasional premature ventricular contractions (PVCs). Her ankles, hands, and eyelids were swollen. Her skin was pale, damp, and cool. She had a spontaneous cough, productive of a small amount of white, frothy sputum. A chest X-ray showed white, fluffy patches that spread outward from the hilar areas to the peripheral borders of both lungs. Her left ventricle appeared moderately enlarged.

The patient's vital signs were blood pressure—183/97 mm Hg, heart rate—101 beats/min, respirations—18 breaths/min and deep, and temperature—37°C. The laboratory report showed that the patient's blood urea nitrogen (BUN), creatinine, potassium, and phosphate levels were all higher than normal. The patient had no urine output. On room air, her arterial blood gas values were pH—7.29, Pa_{CO_2}—32 mm Hg, HCO_3^-—17 mEq/L, and Pa_{O_2}—64 mm Hg. The respiratory therapist started the patient on 4 L/min of oxygen via a nasal cannula and drew a second arterial blood sample 25 minutes later. The results showed a pH of 7.28, Pa_{CO_2}—30 mm Hg, HCO_3^-—16 mEq/L, and Pa_{O_2}—86 mm Hg. No remarkable change was seen in the patient's vital signs.

Although the patient received aggressive medical treatment to correct her cardiac and renal problems, her pulmonary congestion did not significantly improve until she started to produce urine, 24 hours after admission. On day 4, the patient's condition was upgraded. Her skin color was normal, and her skin was warm and dry to the touch. She no longer had a productive cough. When the patient was asked to produce a strong cough, no sputum was produced.

Her peripheral edema was resolved, and her vital signs were blood pressure—132/84 mm Hg, heart rate—74 beats/min, and respiratory rate—10 breaths/min. Her laboratory report showed no remarkable problems, and her ECG was normal. A second chest X-ray showed normal lungs and normal heart size. On room air, her arterial blood gas values were pH—7.39, Pa_{CO_2}—39 mm Hg, HCO_3^-—24 mEq/L, and Pa_{O_2}—93 mm Hg. The patient was discharged on day 5.

Discussion

This case illustrates the adverse effects of poor blood circulation on the function of the kidneys and lungs. Essentially, all of the clinical manifestations in this case can be traced back to the patient's left ventricular failure (a prerenal abnormality). As pointed out in this chapter, prerenal problems are the most common and are generally reversible if identified and treated early. One of the early clinical manifestations of prerenal failure is a sharp reduction in urine output. On admission, the patient had no urine output. With the decline in renal function, the kidney's ability to secrete hydrogen ions (H^+) and to conserve (HCO_3^-) progressively decreases. Furthermore, during the more advanced stages of renal failure, hyperkalemia (increased K^+) is a frequent finding. Thus, because of the increased H^+ and K^+ ion levels and the loss of HCO_3^-, *metabolic acidosis* is an inevitable clinical manifestation in severe renal failure.

Because of the left ventricular failure, fluid progressively accumulated in the patient's lungs and extremities. The fluid accumulation, in turn, increased the density of the alveolar-capillary membranes, causing the white fluffy patches visible on the patient's chest X-ray. In addition, as the fluid accumulation

Clinical Application Case 1 (continued)

in her lungs worsened, the oxygen diffusion across the alveolar-capillary membrane decreased (refer to Figure 4–8). This pathologic process was verified by the $P_{A_{O_2}}$ of 64 mm Hg on admission. Moreover, because the blood flow through the pulmonary system was impeded (because of the left ventricular failure), blood accumulated throughout the patient's extremities, thus causing swelling in the ankles, hands, and eyelids. Fortunately, the patient received aggressive treatment in a timely manner to reverse all of these potentially fatal pathologic processes.

2 Clinical Application Case

A 42-year-old male firefighter was found unconscious in a smoke-filled room on the fourth floor of a burning office building. He had second- and third-degree burns over portions of his left shoulder, left arm, and left hand and over the anterior portion of his chest and abdominal region. His pulse was rapid, and his respiratory rate was slow and gasping. He was quickly carried out of the building and placed in a waiting ambulance. It was later estimated that the patient had been unconscious in the smoke-filled room for more than 10 minutes. En route to the hospital, the patient was manually ventilated with 100 percent oxygen. An intravenous infusion was started, and Ringer's lactated solution was administered. The patient's clothing was cut away, and the burn wounds were covered to prevent shock, fluid loss, and heat loss.

When the patient arrived in the emergency department, the skin that was not burned appeared cherry red. His vital signs were blood pressure—96/55 mm Hg and heart rate—124 beats/min. He was still being manually ventilated with 100 percent oxygen. Bilateral bronchospasm and crackles were heard when his lungs were auscultated. The patient was then intubated. Black, frothy secretions were suctioned from his lungs. A chest X-ray showed white fluffy densities throughout both lung fields. Arterial blood gas values were pH—7.52, Pa_{CO_2}—28 mm Hg, HCO_3^-—22 mEq/L, and Pa_{O_2}—47 mm Hg. His *carboxyhemoglobin* (CO_{Hb}) level was 47 percent. The emergency department physician felt the patient was hypovolemic and going into shock.

The patient was transferred to the intensive care unit and placed on a mechanical ventilator. His progress was stormy during the first 24 hours. The respiratory care team had to make several ventilator adjustments. The patient's hemodynamic profile was classified as critical (see Hemodynamic Profile No. 1). His cardiopulmonary status, however, was finally stabilized on the second day. At this time, the patient's ventilator settings were a ventilatory rate of 12 breaths/min, an inspired oxygen concentration ($F_{I_{O_2}}$) of 1.0, and a positive end-expiratory pressure (PEEP) of 115 cm H_2O. Arterial blood gas values were pH—7.38, Pa_{CO_2}—37 mm Hg, HCO_3^-—24 mEq/L, Pa_{O_2}—78 mm Hg, and Sa_{O_2}—93 percent.

Hemodynamic Profile

Parameter*	Profile No. 1	Profile No. 2
BP	63/39 mm Hg	125/83 mm Hg
CVP	12 mm Hg	3 mm Hg
RAP	13 mm Hg	3 mm Hg
$\overline{\text{PAP}}$	25 mm Hg	14 mm Hg
CO	2.7 L/min	5.8 L/min
Urine Output	0 mL/hr	54 mL/hr

*BP = blood pressure; CVP = central venous pressure; RAP = right atrial pressure; $\overline{\text{PAP}}$ = mean pulmonary artery pressure; CO = cardiac output.

Two days later, the patient's cardiopulmonary status was upgraded to fair. His ventilator settings at this time were 6 breaths/min, $F_{I_{O_2}}$—0.5, and PEEP—18 cm H_2O. Arterial blood gas values were pH—7.41, Pa_{CO_2}—38 mm Hg, HCO_3^-—24 mEq/L, Pa_{O_2}—84 mm Hg, and Sa_{O_2}—93 percent. His carboxyhemoglobin (CO_{Hb}) level was 11 percent. His hemodynamic status had significantly improved, and he was producing urine

(*continued*)

Clinical Application Case 2 (continued)

(see Hemodynamic Profile No. 2). The patient progressively improved and was discharged 2 weeks later.

Discussion

Similar to Case 1, this case illustrates a prerenal abnormality. The patient's burns caused fluid sequestration, which in turn lead to *hypovolemia* (see Table 16–3). As a result of the hypovolemia, the blood flow though the patient's kidneys decreased. Again, one of the early clinical manifestations of prerenal failure is a sharp reduction in urine output. Note the low cardiac output and no urine output charted on Hemodynamic Profile No.1. Fortunately, the patient responded favorably to therapy, and his hemodynamic status and urine output returned to normal (see Hemodynamic Profile No. 2).

Note also that the patient's pulmonary status, unrelated to the poor kidney function, was very serious on admission. The patient's pathologic lung changes in the distal airways and alveoli were most likely caused by the irritant and toxic gases and suspended soot particles associated with incomplete combustion and smoke. Many of the substances found in smoke are extremely caustic to the tracheobronchial tree and poisonous to the body. The injuries that develop from smoke inhalation include inflammation of the tracheobronchial tree, bronchospasm, excessive bronchial secretions and mucus plugging, decreased mucosal ciliary transport mechanism, atelectasis, alveolar edema, and frothy secretions. Evidence of this condition was documented by the white, fluffy densities found throughout both lung fields and the low Pa_{O_2} (47 mm Hg) at admission. Finally, the patient's carbon monoxide level (CO_{Hb}—47 percent) was dangerously high in the emergency department. Although the patient initially responded slowly to respiratory care, the described pathologic processes were ultimately reversed, and the cardiopulmonary status was normal at the time of discharge.

Review Questions

1. The outer one-third of the kidney is called the

A. Medulla
B. Minor calyces
C. Renal pyramid
D. Cortex

2. Glomerular filtration is directly proportional to

A. Blood cell size
B. Hydrostatic pressure
C. Osmotic pressure
D. The patient's fluid intake

3. Tubular reabsorption occurs primarily in the

A. Renal corpuscle
B. Proximal convoluted tubule
C. Loop of Henle
D. Distal convoluted tubule

4. The major substance(s) transported by means of tubular secretion is (are)

1. H^+
2. Cl^-
3. K^+
4. HCO_3^-
5. Na^+

    A. 1 only
    B. 2 and 4 only
    C. 4 and 5 only
    D. 1 and 3 only

5. The urine produced by the healthy kidney has a specific gravity of about

A. 1.000–1.001
B. 1.006–1.020
C. 1.003–1.030
D. 1.060–1.080

6. Which of the following can be classified as a prerenal condition?

1. Heart failure
2. Intratubular obstruction
3. Bladder outlet obstruction
4. Hypovolemia

    A. 2 only
    B. 4 only
    C. 2 and 3 only
    D. 1 and 4 only

7. Which of the following are the functional units of the kidneys?

A. Collecting ducts
B. Major calyces
C. Peritubular capillaries
D. Nephrons

8. Which of the following empties urine into the bladder?

A. Collecting ducts
B. Ureters
C. Distal convoluted tubules
D. Urethra

9. Normally, the net glomerular filtration pressure is about

A. 5 mm Hg
B. 10 mm Hg
C. 15 mm Hg
D. 20 mm Hg

10. Which of the following is(are) part of the nephron?

1. Proximal convoluted tubules
2. Loop of Henle
3. Glomerulus
4. Distal convoluted tubules

A. 3 only
B. 2, 3, and 4 only
C. 1, 2, and 3 only
D. 1, 2, 3, and 4

Clinical Application Questions

Case 1

1. In this case, all of the clinical manifestations can be traced back to the patient's ____________

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____

2. What was the early clinical manifestation of prerenal failure presented?

____

____

____

3. Why did metabolic acidosis develop? ____________

____

____

4. What clinical manifestations developed as a result of left ventricular failure? ____________

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____

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Case 2

1. What was the cause of the prerenal abnormality in this case? ____________

____

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2. What lung injuries developed as a result of smoke inhalation? ____________

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3. What was the clinical evidence that the lung injuries listed in question 2 were present?

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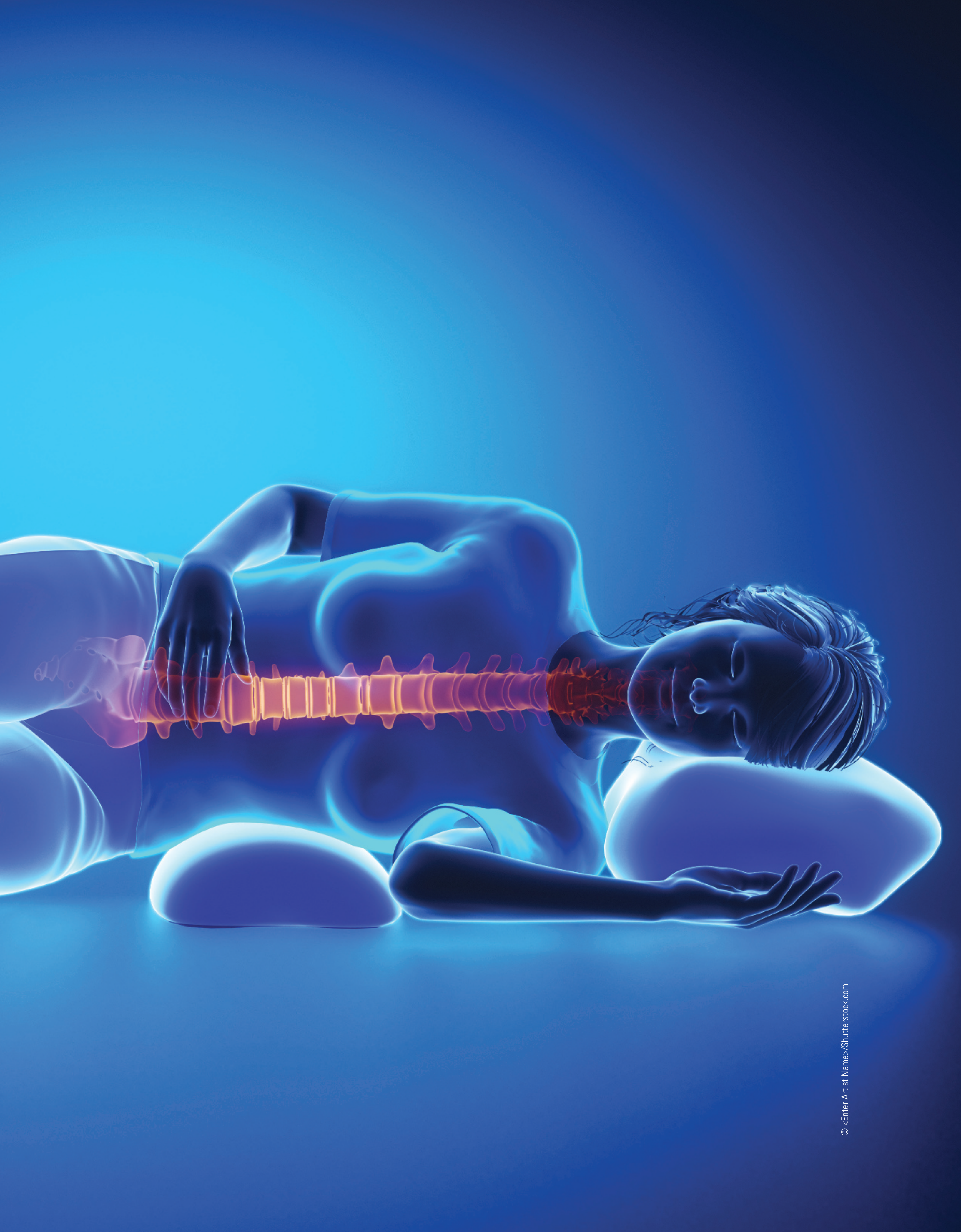

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CHAPTER 17

Sleep Physiology and Its Relationship to the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Differentiate sleep from a coma.
2. Define polysomnography.
3. Define a polysomnogram epoch.
4. Describe the purpose of the following monitors: electroencephalogram (EEG), electro-oculogram (EOG), electromyogram (EMG), oximeter, and CO_2 analyzer.
5. Differentiate among the various EEG waveforms.
6. Identify the major epoch physiologic components associated with each type of sleep.
7. Outline the normal sleep cycle.
8. Describe the two most widely accepted theories regarding the purpose of sleep.
9. Describe circadian rhythms.
10. Describe the normal sleep patterns for the following groups: newborns and infants, toddlers and preschoolers, children and adolescents, and young adults and older adults.
11. List factors that affect sleep initiation and maintenance.
12. Describe common sleep disorders.
13. Describe the physiologic changes that occur during sleep.

Introduction

Sleep is a naturally occurring state of partial unconsciousness, diminished activity of the skeletal muscles, and depressed metabolism from which a person can be awakened by stimulation. Because sleep is readily reversible, it is distinguished from a *coma,* which is a state of unconsciousness from which a person cannot be awakened—even by the most forceful stimuli. Interestingly, an individual's environmental monitoring often continues to function during sleep, as illustrated by the fact that a strong stimulus—like a baby's cry—can immediately awaken a parent. In fact, it is well documented that individuals who sleepwalk can actually navigate around objects or climb stairs while truly asleep.

All mammals and birds sleep. Body size appears to play an important role in determining the amount of sleep a species needs. In general, large mammals need less sleep than small mammals. For example, a giraffe or elephant sleeps about 3 to 4 hours a day, whereas a cat or ferret needs about 12 to 14 hours of sleep a day. Bats, opossums, and armadillos sleep 18 or more hours a day. The newborn requires about 17 hours of sleep a day, whereas the adult needs about 6 to 8 hours a day.

During the past several years, there has been a tremendous increase in the demand for sleep medicine diagnostic and therapeutic services—driven, in part, by (1) the heightened appreciation of sleep disorders in the general population and (2) the increased scientific research studies now available concerning sleep and sleep disorders. In response to the increased need for these services, many specialized sleep centers and laboratories are now available throughout the health care industry. These sleep centers offer **polysomnography** (sleep studies) with qualified sleep technologists who provide many diagnostic and therapeutic services.

An **epoch** or **polysomnogram** is a recorded measurement of time during a sleep study of multiple physiologic variables that can be used to identify the different phases of sleep and, importantly, sleep disorders. For example, sleep-related disorders, such as *obstructive sleep apnea,* are now known to adversely affect the cardiopulmonary system in numerous ways, and the respiratory therapist commonly treats them.

The major physiologic variables provided during a polysomnogram include (1) an **electroencephalogram** (EEG), which measures the electrophysiologic changes in the brain; (2) an **electro-oculogram** (EOG), which monitors the movements of the eyes; and (3) an **electromyogram** (EMG), which measures muscle activity. Table 17–1 provides an overview of common EEG waveforms. Other physiologic features typically monitored during a sleep study include (1) the presence or absence of snoring, (2) nasal and oral airflow, (3) chest movement, (4) abdomen movement, (5) Sa_{O_2}, and (6) an electrocardiogram (ECG). End-tidal CO_2 monitoring as a surrogate for airflow is used in sleep studies of neonates and infants and more and more often in adults. Thermistors, which sense change in temperature (exhaled air is warmer than inspired air), are also used for this purpose.

Figure 17–1 provides a representative sleep study epoch of a patient with "eyes open and awake." Most sleep study epochs are 30 seconds in duration. Thus, between 720 and 960 separate epoch recordings are generated over a 6- to 8-hour sleep study period.

FIGURE 17-1 Eyes open—wake. As shown in the yellow bar, the EEG records beta waves with high-frequency, low-amplitude activity and sawtooth waves. EOG is low frequency and variable, and the EMG activity is relatively high. The epoch appears similar to REM sleep.

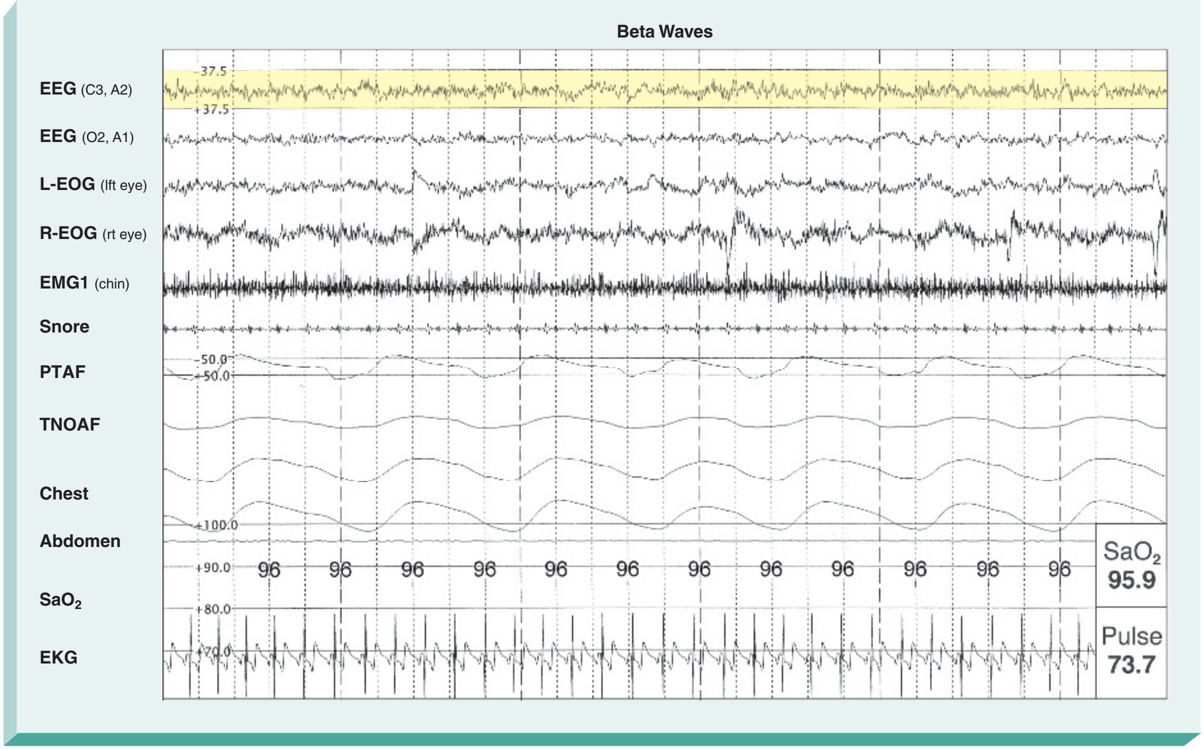
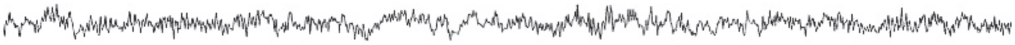
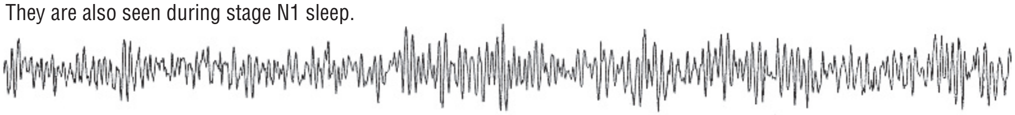
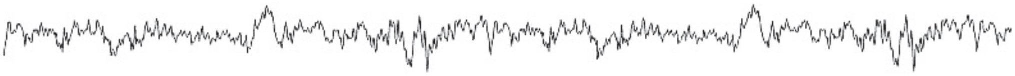
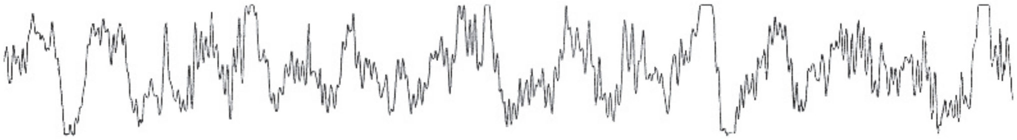
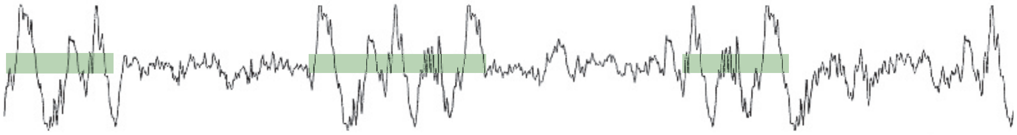
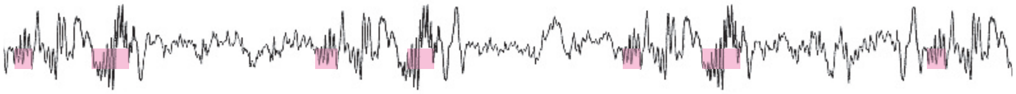
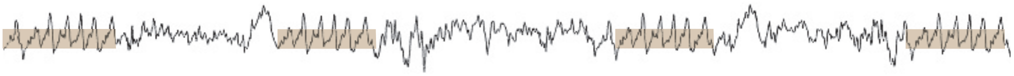
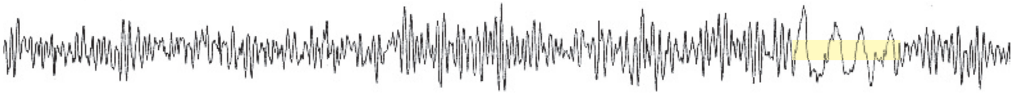


TABLE 17-1 Common EEG Waveforms

An electroencephalogram (EEG) measures the electrophysiologic changes in the brain. The EEG electrical activity is characterized by frequency in cycles per second or hertz (Hz), amplitude (voltage), and the direction of major defection (polarity). The following are the most common frequency ranges.

Beta Waves (>13 Hz)	 One of the four brain waves, characterized by relatively low voltage or amplitude and a frequency greater than 13 Hz. Beta waves are known as the "busy waves" of the brain. They are recorded when the patient is awake and alert with eyes open. They are also seen during stage N1 sleep.
Alpha Waves (8–13 Hz)	 One of the four brain waves, characterized by a relatively high voltage or amplitude and a frequency of 8–13 Hz. Alpha waves are known as the "relaxed waves" of the brain. They are commonly recorded when the individual is awake, but in a drowsy state and when the eyes are closed. Alpha waves are commonly seen during stage N1 sleep. Bursts of alpha waves are also seen during brief awakenings from sleep called arousals. Alpha waves may also be seen during REM sleep.
Theta Waves (4–7 Hz)	 One of the four types of brain waves, characterized by a relatively low frequency of 4–7 Hz and low amplitude of 10 microvolts (μV). Theta waves are known as the "drowsy waves" of the brain. They are seen when the individual is awake but relaxed and sleepy. They are also recorded in stage 1 sleep, in REM sleep, and as background waves during stage N2 sleep.
Delta Waves (<4 Hz)	 The slowest of the four types of brain waves. Delta waves are characterized by a frequency of less than 4 Hz and high-amplitude (>75 μV) broad waves. Although delta EEG activity is usually defined as <4 Hz, in human sleep scoring, the slow-wave activity used for staging is defined as EEG activity <2 Hz (>0.5 second duration) and a peak-to-peak amplitude of >75 μV. Delta waves are called the "deep-sleep waves." They are associated with a dreamless state from which an individual is not easily aroused. Delta waves are seen primarily during stage N3 sleep.
K Complexes	 K complexes are intermittent, high-amplitude, biphasic waves of at least 0.5-second duration that signal the start of stage N2 sleep (green bars). A K complex consists of a sharp negative wave (upward deflection), followed immediately by a slower positive wave (downward deflection), that is >0.5 second. K complexes are usually seen during stage N2 sleep. They are sometimes seen in stage N3. Sleep spindles are often superimposed on K complexes.
Sleep Spindles	 Sleep spindles are sudden bursts of EEG activity in the 12–14 Hz frequency (6 or more distinct waves) and duration of 0.5 to 1.5 seconds (pink bars). Sleep spindles mark the onset of stage N2. They may be seen in stage N3, but usually do not occur in REM sleep.
Sawtooth Waves	 Sawtooth waves are notched-jagged waves of frequency in the theta range (3–7 Hz) (brown bars). They are commonly seen during REM sleep. Although sawtooth waves are not part of the criteria for REM sleep, their presence is a clue that REM sleep is present.
Vertex Waves	 Vertex waves are sharp negative (upward deflection) EEG waves, often in conjunction with high amplitude and short (27 Hz) activity (yellow bar). The amplitude of many of the vertex sharp waves are greater than 20 μV, and occasionally, they may be as high as 200 μV. Vertex waves are usually seen at the end of stage N1.

Types of Sleep

Non-rapid-eye-movement sleep (non-REM sleep or NREM sleep) and **rapid-eye-movement sleep** (REM sleep) are the two major types of sleep. The following subsections provide a more in-depth discussion of the two major types of sleep and the physiologic changes commonly observed during a full sleep cycle.

Clinical Connection 17-1

The Sleep Disorder Specialist—Trends, Education, and Certification

The respiratory therapist can further broaden his or her career by pursuing additional education and training as a **sleep disorder specialist (SDS)** (Figure 17–2). The SDS performs sleep tests and works with physicians to provide a variety of information needed for the diagnosis of sleep disorders. For example, the SDS:

- Monitors brain waves, eye movements, muscle activity, multiple breathing variables, and blood oxygen levels during sleep, using specialized recording equipment.
- Interprets the recording as it happens and responds appropriately to emergencies.
- Instructs the patient in recording and maintaining a sleep diary of 7 to 14 days of wake/sleep cycles.
- Provides support services related to the treatment of sleep-related problems, including helping patients use devices for the treatment of breathing problems during sleep and helping individuals develop good sleep habits.

FIGURE 17-2 A sleep disorder specialist.

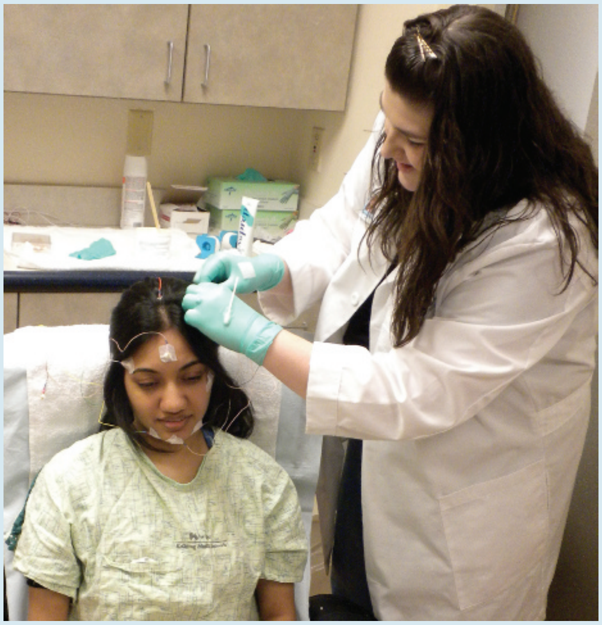


Image courtesy of Dr. George Burton

The **National Board for Respiratory Care Inc. (NBRC)** administers the credentialing examination for the sleep disorder specialist. The NBRC's Sleep Disorder Specialty examination program is designed for a respiratory therapist with an NBRC respiratory care credential and experience or education in the field of sleep medicine. The admission requirements are the following:

- Be a certified respiratory therapist (CRT) or registered respiratory therapist (RRT) having completed a Commission on Accreditation for Respiratory Care (CoARC) or Committee on Accreditation Allied Health Education Programs (CAAHEP) accredited respiratory therapist program, including a sleep add-on track.
- Be a CRT with 6 months of full-time[1] clinical experience following certification in a sleep diagnostics and treatment setting under medical supervision (MD, DO, or PhD).
- Be an RRT with 3 months of full-time clinical experience following certification in a sleep diagnostic and treatment setting under medical supervision.

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[1] Full-time experience is defined as a minimum of 21 hours per week per calendar year in a sleep diagnostics and treatment setting under medical supervision following certification acceptable to the Board. Clinical experience must be completed before the candidate applies for this examination (http://www.nbrc.org).

Eyes Open—Wake

The **eyes open—wake** state (stage W) appears very similar to REM sleep. The EEG shows **beta waves** with high frequency, low-amplitude activity, and **sawtooth waves**. The EOG is low frequency and variable, and the EMG activity is relatively high (see Figure 17–1).

Eyes Closed—Wake

The EEG during the **eyes closed—wake** (drowsy) period is characterized by prominent **alpha waves** (>50 percent). The EOG tracing usually shows slow, rolling eye movements, and the EMG activity is relatively high (Figure 17–3).

Non-REM Sleep (N Sleep)

Non-REM sleep consists of three stages of sleep. In general, **stage N1** and **stage N2** are described as *light sleep stages,* and **stage N3** is referred to as *slow-wave sleep* and *deep sleep.* Non-REM sleep accounts for about 75 to 80 percent of sleep time in the average adult. During the first 30 to 45 minutes of sleep, an individual passes through all three stages of non-REM sleep, progressively moving toward slow-wave sleep—stage N3. In the average young adult, stage N1 comprises about 3 to 8 percent of sleep time, stage N2 about 45 to 55 percent, and stage N3 makes up about 15 to 20 percent of total sleep time. The following is a general overview of the three stages of non-REM sleep.

FIGURE 17-3 Eyes closed—wake. As shown in the purple bar, the EEG records prominent alpha waves (>50 percent). The EOG tracing often shows slow, rolling eye movements, and the EMG activity is relatively high.

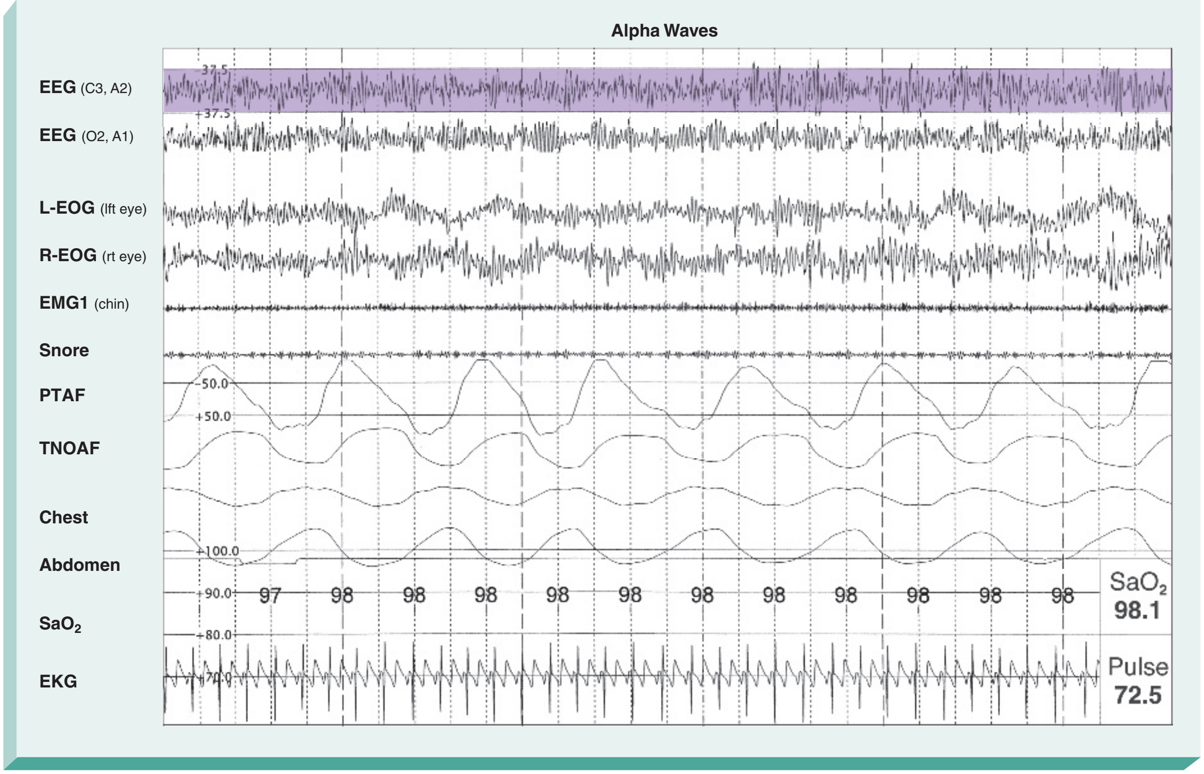
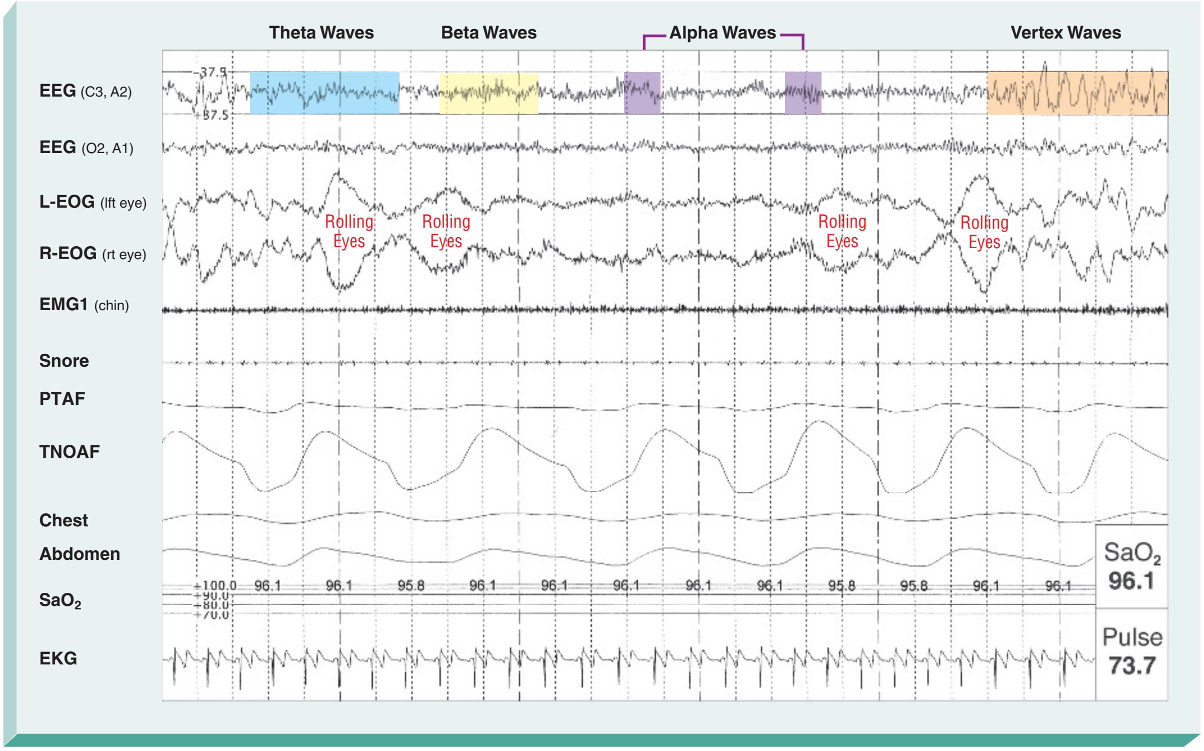

Alpha Waves
EEG (C3, A2)
EEG (O2, A1)
L-EOG (lft eye)
R-EOG (rt eye)
EMG1 (chin)
Snore
PTAF
TNOAF
Chest
Abdomen
SaO₂
EKG
-37.5
+37.5
-50.0
+50.0
+100.0
+90.0
+80.0
+70.0
97
98
98
98
98
98
98
98
98
98
98
98
SaO₂
98.1
Pulse
72.5

FIGURE 17-4 Stage N1 non-REM sleep. EEG records low-voltage, mixed-frequency activity, with alpha waves (8–12 Hz, $<$50 percent) (purple bar) and theta waves (blue bar). Some beta waves ($>$13 Hz) (yellow bar) may also appear. Vertex waves commonly appear toward the end of stage N1 (orange bar). The EOG shows slow, rolling eye movements. The EMG reveals decreased activity and muscle relaxation. Respirations become regular, and the heart rate and blood pressure decrease slightly. Snoring may occur.



Stage N1

Stage N1 is the transitional stage between drowsiness and sleep. The person feels sleepy and often experiences a drifting or floating sensation. The sleeper may experience sudden muscle contractions called **hypnic myoclonia**. These contractions are frequently preceded by a sensation of starting to fall. These sudden muscle movements are similar to the "jump" one elicits when startled. Under normal conditions, stage N1 lasts between 10 to 12 minutes and is very light sleep. A person can be easily awakened during this period.

As the person moves into stage N1, the EEG shows light sleep comprised of low-voltage, mixed-frequency activity, with **alpha waves** (8–12 Hz[2]; $<$50 percent) and **theta waves**. Alpha waves indicate that the brain is in a calm and relaxed state of wakefulness. Some **beta waves** ($>$13 Hz) may also appear. **Vertex waves** commonly appear toward the end of stage N1. The EOG shows slow, rolling eye movements. The EMG reveals decreased activity and muscle relaxation. Breathing become regular, and the heart rate and blood pressure decrease slightly ("nocturnal dipping"). Minute ventilation, cerebral blood flow, and muscle tone diminish. Snoring may occur. If awakened, persons may state that they were not asleep (Figure 17–4).

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[2] Hz = 5 cycles per second.

Stage N2

Stage N2 is still a relatively light sleep stage, although arousal is a bit more difficult. The EEG becomes more irregular and is comprised predominantly of **theta waves** (4–7 Hz), intermixed with sudden bursts of **sleep spindles** (12–18 Hz) and one or more **K complexes**. **Vertex waves** may also be seen during this stage. The EOG shows either slow eye movements or absence of slow eye movements. The EMG has low electrical activity. The heart rate, blood pressure, respiratory rate, and temperature decrease slightly. Snoring may occur. Stage N2 occupies the greatest proportion of the total sleep time and accounts for about 40 to 50 percent of sleep. If awakened, the person may say he or she was thinking or daydreaming (Figure 17–5).

Stage N3

Stage N3 sleep can be divided into the following two main categories: (1) slow-wave sleep and (2) deep sleep.

Stage N3—slow-wave sleep. *Slow-wave sleep* is present when 20 to 50 percent of the EEG activity consists of high-amplitude ($>75\ \mu$V), slow-frequency (2 Hz or slower) **delta waves**. Both **sleep spindles** and **K complexes** may be present during this period of stage N3. There is little or no eye movement on the EOG, and the EMG activity is low. The skeletal muscles are very relaxed, but tone is maintained. There is a continued

FIGURE 17-5 Stage N2 non-REM sleep. The EEG becomes more irregular and is comprised mostly of theta waves (4–7 Hz) (blue bar), intermixed with sudden bursts of sleep spindles (12–18 Hz) (pink bar), and one or more K complexes (green bars). Vertex waves may also be seen during this stage (yellow bar). The EOG shows either slow eye movements or absence of slow eye movements. The EMG has low electrical activity. The heart rate, blood pressure, respiratory rate, and temperature decrease slightly. Snoring may occur.

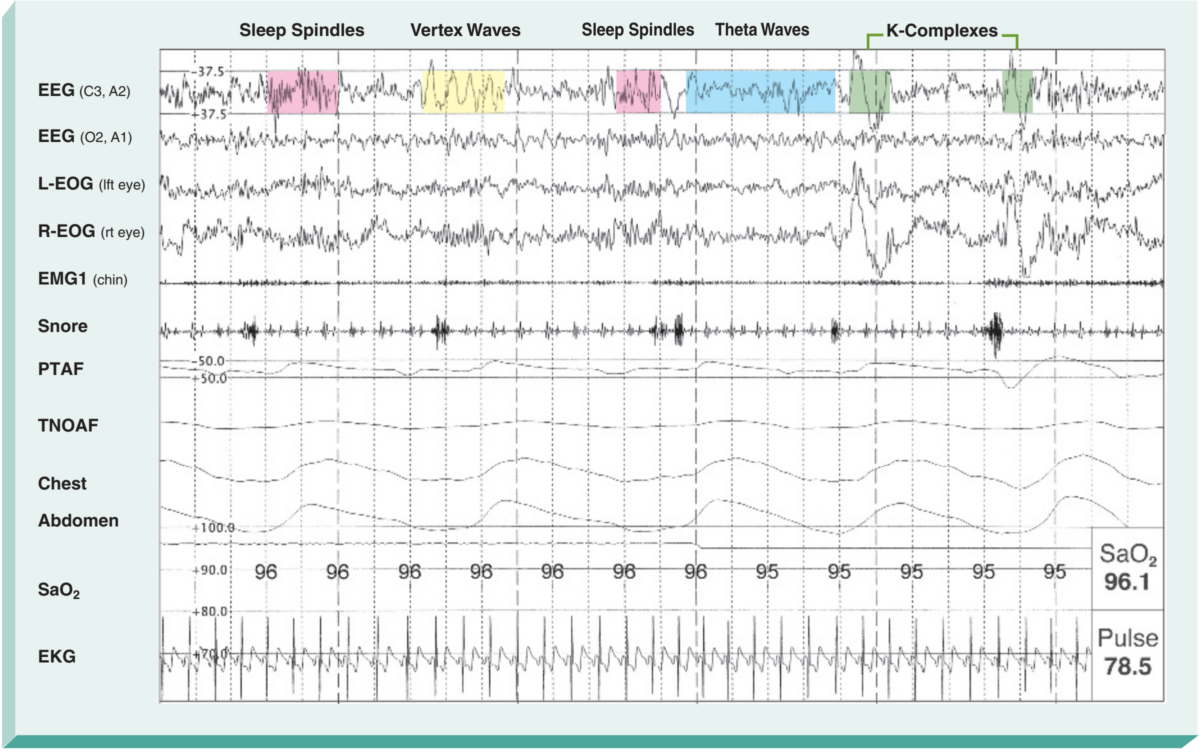
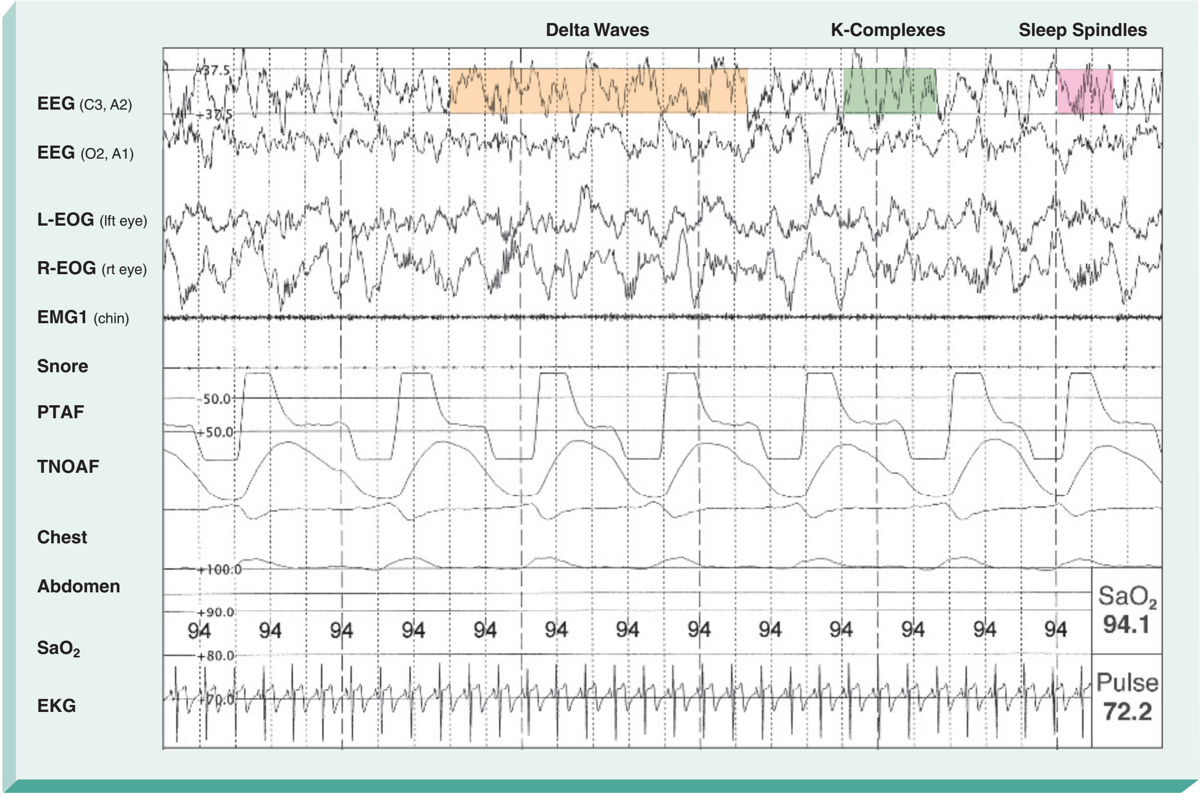


FIGURE 17-6 Stage N3 non-REM (slow-wave) sleep. EEG records 20 to 50 percent activity of high-amplitude (>75 μV), slow-frequency (2 Hz or slower) delta waves (orange bar). Sleep spindles (pink bar) and K complexes (green bar) may be present during stage N3. The EOG records little or no eye movement, and the EMG activity is low. There is a continued decrease in the heart rate, blood pressure, respiratory rate, body temperature, and oxygen consumption. Snoring may occur.



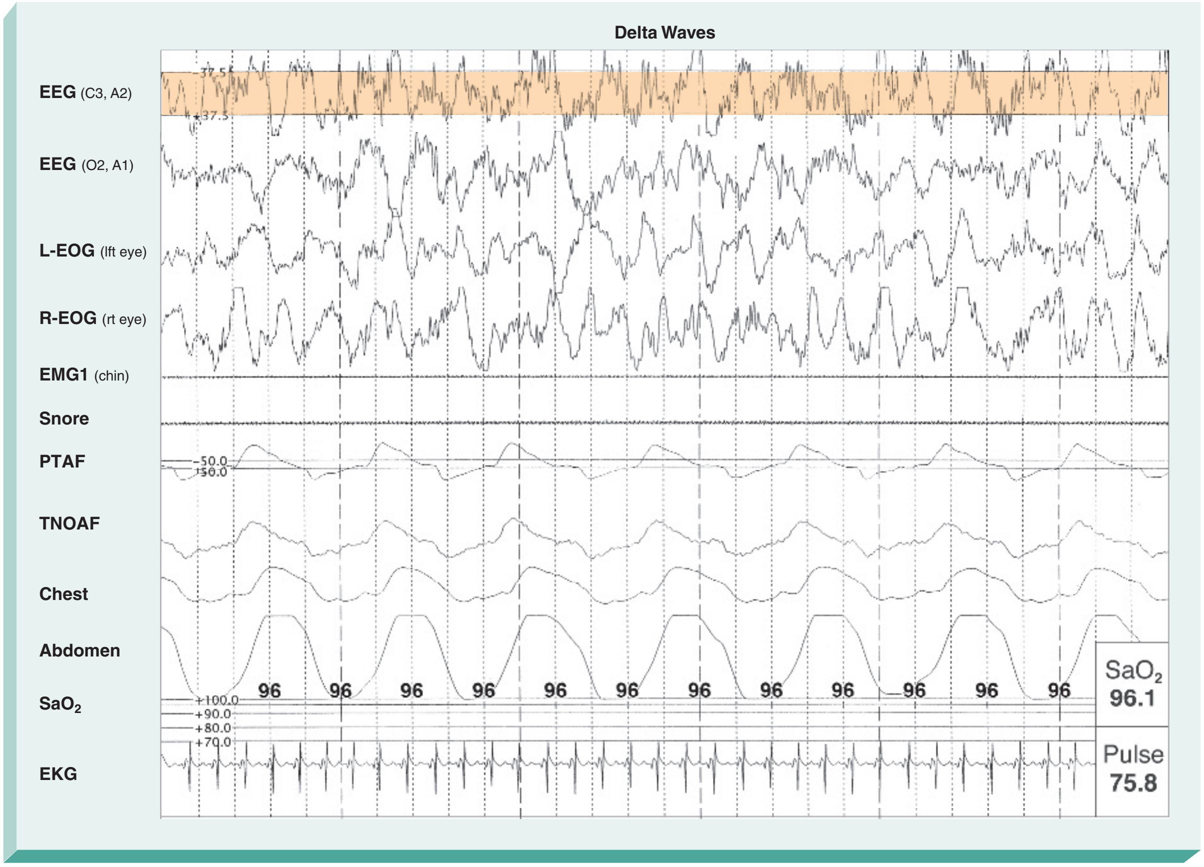
decrease in the heart rate, blood pressure, respiratory rate, body temperature, and oxygen consumption. Snoring may occur. Dreaming may occur, but is less dramatic, more realistic, and may lack plot. The sleeper becomes more difficult to arouse. Stage N3 is usually reached about 20 to 25 minutes after the onset of stage N1 (Figure 17–6).

Stage N3—deep sleep. *Deep sleep* is present when more than 50 percent of the EEG activity consists of **delta waves** (amplitude >75 μV and frequency 2 Hz or less). The EOG shows no eye movements, and the EMG has little or no electrical activity. The sleeper is very relaxed and seldom moves. The vital signs reach their lowest, normal level. In fact, the sleeper's heart and respiratory rate are generally decreased 20 to 30 percent below his or her normal waking-hour levels. Oxygen consumption is low. The sleeper is very difficult to awaken. This period of stage N3 is thought to be important for mental and physical restoration. This is the stage in which bed-wetting, night terrors, and sleepwalking are most likely to occur (Figure 17–7).

REM Sleep

REM sleep resembles the eyes open—wake state. The EEG reveals low-voltage, mixed EEG activity, and frequent **sawtooth waves**. **Alpha waves** may be present. The EOG shows REM. The EMG recording shows low electrical activity, and a temporary paralysis of most of the skeletal muscles (e.g., arms, legs) is present.

FIGURE 17-7 Stage N3 non-REM (deep) sleep. EEG records more than 50 percent activity of delta waves (amplitude >75 μV frequency 2 Hz or less) (orange bar). The EOG shows no eye movements, and the EMG has little or no electrical activity. The sleeper's heart and respiratory rate are generally decreased 20 to 30 percent below normal waking-hour levels.



Diaphragmatic muscle activity continues. During REM sleep, brain metabolism may increase as much as 20 percent. The breathing rate increases and decreases irregularly. The heart rate becomes inconsistent with episodes of increased and decreased rates. Snoring may or may not present. When the sleeper is very tired, the duration of each REM period is very short or even absent. As the person becomes more rested through the sleep period, the length of the REM sleep periods increase.

About 25 percent of the sleep of the young normal adult consists of REM sleep. The first REM sleep period usually occurs about 70 to 90 minutes after one falls asleep and lasts 5 to 30 minutes. REM is not as restful as NREM sleep. In fact, REM sleep is also known as **paradoxic sleep** because the EEG pattern is similar to the normal awake pattern. Most dreams occur during REM sleep. They are frequently remembered during the wakeful state and are often described as having vivid content, full color, sounds, implausible or bizarre settings, and a sense of paralysis (Figure 17–8).

Table 17–2 summarizes the sleep stages, according to the current American Academy of Sleep Medicine standards.[3]

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[3] *The AASM Manual for the Scoring of Sleep & Associated Events: Rules, Terminology, and Technical Specifications.*

FIGURE 17-8 REM sleep. Resembles the eyes open—wake epoch. The EEG records low-voltage, mixed EEG activity and frequent sawtooth waves (brown bar). Alpha waves may be present (purple bar). The EOG records rapid eye movement (REM). The EMG records low electrical activity and documents a temporary paralysis of most of the skeletal muscles (e.g., arms, legs). The breathing rate increases and decreases irregularly. During REM sleep, the heart rate becomes inconsistent with episodes of increased and decreased rates. Snoring may or may not be present. REM is not as restful as NREM sleep. REM is also known as paradoxic sleep. Most dreams occur during REM sleep.

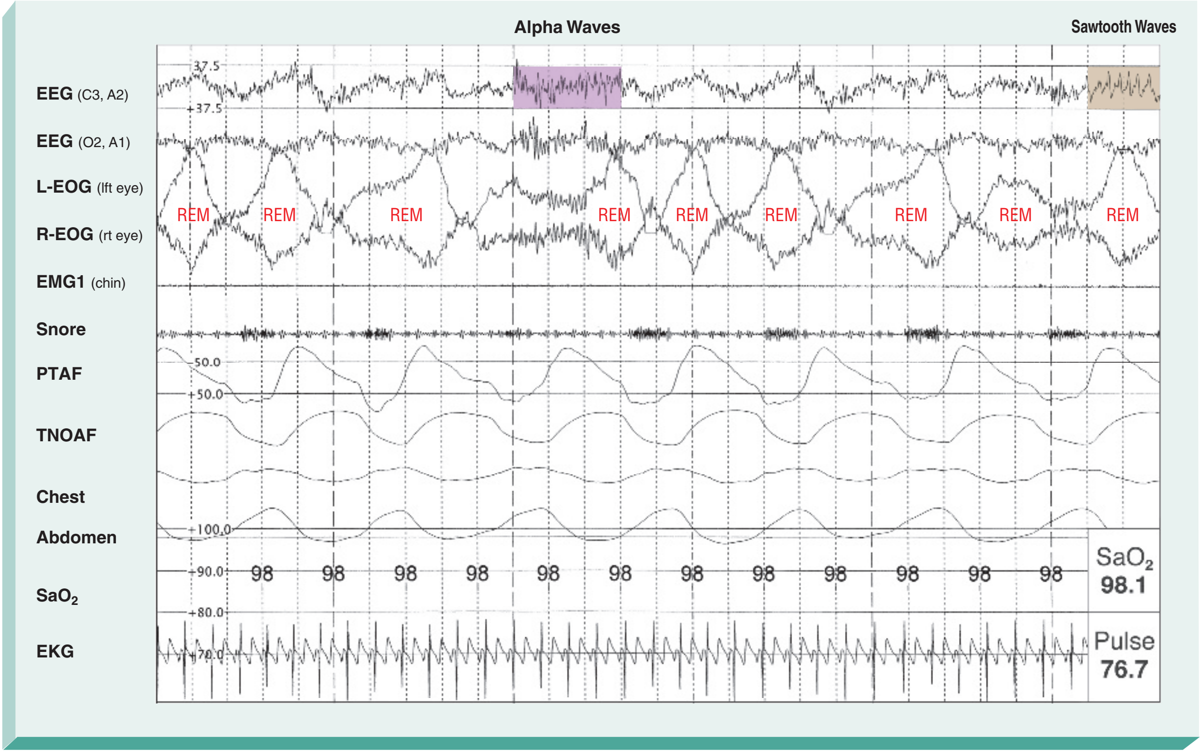
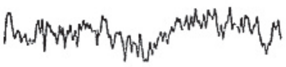
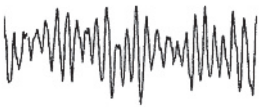
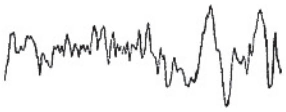
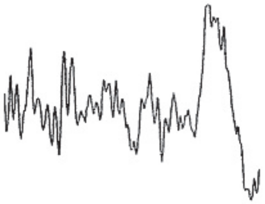
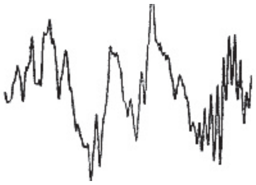
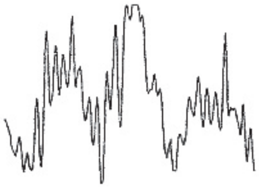
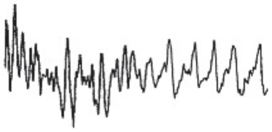

Alpha Waves
Sawtooth Waves
EEG (C3, A2)
EEG (O2, A1)
L-EOG (lft eye)
R-EOG (rt eye)
EMG1 (chin)
Snore
PTAF
TNOAF
Chest
Abdomen
SaO_2
EKG
37.5
+37.5
REM
REM
REM
REM
REM
REM
REM
REM
REM
50.0
+50.0
+100.0
+90.0
98
98
98
98
98
98
98
98
98
98
98
98
+80.0
+70.0
SaO_2
98.1
Pulse
76.7

TABLE 17-2 Sleep Stages

STAGE	EEG	CHARACTERISTICS
Eyes Open—Wake		The EEG shows **beta waves**, and high-frequency, low-amplitude activity. The EOG looks very similar to REM sleep waves—low amplitude, mixed frequency, and sawtooth waves. EMG activity is relatively high.
Eyes Closed—Wake (drowsy)		The EEG is characterized by prominent **alpha waves** (>50%). The EOG shows slow, rolling eye movements, and the EMG activity is relatively high.
NON-RAPID EYE MOVEMENT (NON-REM SLEEP)		
Stage N1 (light sleep)		The EEG shows low-voltage, mixed-frequency activity, **alpha waves** (8–12 Hz, <50%), and **theta waves**. Some **beta waves** (>13 Hz) may also appear. **Vertex waves** commonly appear toward the end of stage N1. The EOG shows slow, rolling eye movements. The EMG reveals decreased activity and muscle relaxation. Respirations become regular and the heart rate and blood pressure decrease slightly. Snoring may occur. If awakened, the person may state that they were not asleep.

(continued)

TABLE 17-2 Sleep Stages *(continued)*

Stage N2 (light sleep)		The EEG becomes more irregular and is comprised predominantly of **theta waves** (4–7 Hz), intermixed with sudden bursts of **sleep spindles** (12–18 Hz), and one or more **K complexes**. **Vertex waves** may also be seen during this stage. The EOG shows either slow eye movements or absence of slow eye movements. The EMG has low electrical activity. The heart rate, blood pressure, respiratory rate, and temperature decrease slightly. Snoring may occur. If awakened, the person may say they were thinking or daydreaming.
Stage N3 (slow-wave sleep)		EEG shows 20%–50% **delta waves**. Both **sleep spindles** and **K complexes** may be present. EOG shows little or no eye movement, and the EMG activity is low. There is a continuous decrease in the heart rate, blood pressure, respiratory rate, body temperature, and oxygen consumption. Snoring and dreaming may occur and the sleeper becomes more difficult to arouse.
Stage N3 (deep sleep)		EEG shows more than 50% **delta waves**. The EOG shows no eye movements, and the EMG has little or no electrical activity. The sleeper is very relaxed and seldom moves. The vital signs reach their lowest, normal level. Oxygen consumption is low. The patient is very difficult to awaken. Bed-wetting, night terrors, and sleepwalking may occur.
RAPID EYE MOVEMENT (REM)		
		About 90 minutes into the sleep cycle, there is an abrupt EEG pattern change. The EEG pattern resembles the wakeful state with low voltage, mixed EEG activity. **Sawtooth waves** are frequently seen. **Alpha waves** may be seen. The respiratory rate increases and is irregular and shallow. The heart rate and blood pressure increase. Rapid eye movement occurs and there is paralysis of most skeletal muscles. Most dreams occur during REM sleep.

Clinical Connection 17-2

Types of Sleep Studies

The majority of sleep studies are done in sleep disorders centers, which may be "facility-based" (associated with hospitals) or freestanding (Figure 17–9). In some settings, limited studies may be done in the home. In fully accredited sleep disorders centers, the following tests are commonly performed:

- **Nocturnal polysomnography** (nights). **Polysomnography** (PSG), also known as a **sleep study**, is a study of sleep. The test result is called a **polysomnogram**, also abbreviated as PSG. The results of the PSG are used as a diagnostic tool in sleep medicine. The PSG monitors many body functions including brain activities (EEG), eye movements (EOG), muscle activity or skeletal muscle activation (EMG), respiratory airflow, pulse oximetry, expired CO_2, and heart rhythm (ECG) during sleep.
- **Multiple sleep latency testing** (MSLT) (days). The MSLT is used to measure the time elapsed from the start of a daytime nap period to the first signs of sleep, called **sleep latency**. The test is based on the idea that the more sleepier people are, the faster they will fall asleep. The MSLT can be used (1) to test for **narcolepsy**, (2) to test for physical tiredness versus true excessive daytime sleepiness, and (3) to determine if treatments for breathing disorders are working. The primary purpose of MSLT is to serve as an objective measure of sleepiness. The test consists of four or five 20-minute nap opportunities that are scheduled about 2 hours apart. A MSLT is usually performed after an overnight sleep study. During the test, the patient's brain waves (EEG), muscle activity (EMG), and eye movements (EOG) are recorded.

(Continued)

Clinical Connection 2-1, Continued

- **Maintenance of wakefulness testing (MWT)** (nights or days, depending on work time being studied). The MWT is used to evaluate how alert an individual is during the day. The MWT determines whether or not a patient is able to stay awake for a defined period of time. The test indicates how well an individual is able to function and remain alert during periods of quiet time and inactivity.

Home sleep tests (HSTs) may be used solely for the diagnosis of sleep apnea. Portable equipment is set up in the patient's home with limited channels to monitor airflow, respiratory effort, and pulse oximetry.

FIGURE 17-9 Nocturnal polysomnography (sleep study).

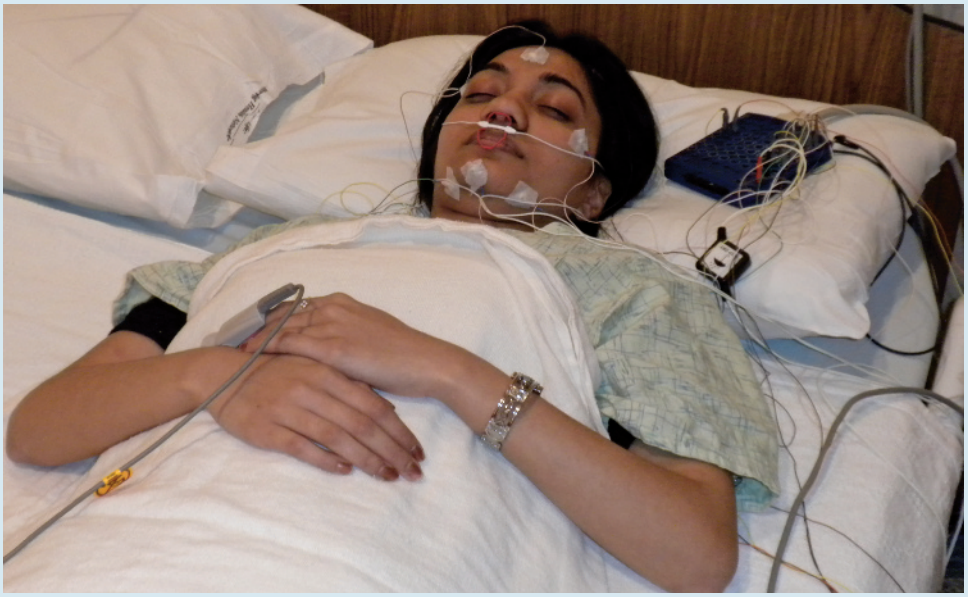


Image courtesy of Dr. George Burton

Normal Sleep Cycles

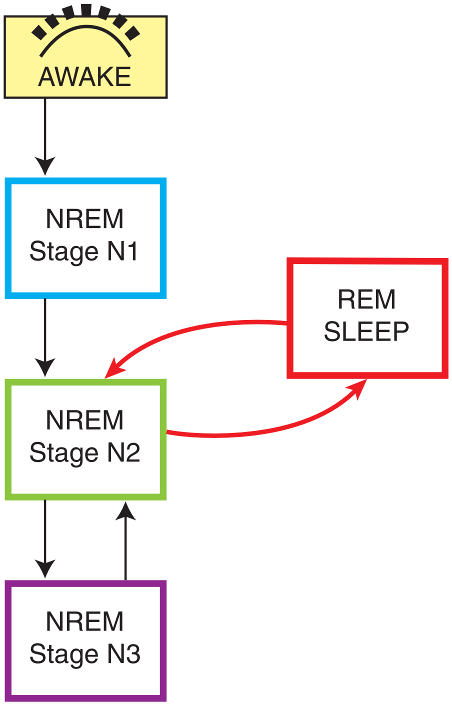
Under normal circumstances, most people require 10 to 30 minutes to fall asleep. The time needed to fall asleep is called **sleep latency**. A sleep latency period of less than 5 minutes indicates excessive sleepiness; a sleep latency period of longer than 30 minutes is associated with the lack of sleepiness, emotional stress, environmental disturbances, medication, illness, or pain.

One full sleep cycle begins with stage N1. The sleeper then progresses through stages N2 and N3 (slow-wave sleep and deep sleep), followed by a return to stage N2. From stage N2, the sleeper slips into REM sleep. The end of the first REM sleep cycle is the conclusion of the first sleep cycle.

From REM sleep, the individual moves back to stage N2, and a new sleep cycle starts (Figure 17–10). The duration of each sleep cycle is about 90 to 110 minutes. The sleep cycles become longer as the sleeper becomes rested. Between four to six full cycles of sleep occur during a normal night's sleep.

The normal young adult moves from stages N1 to N3 in about 30 minutes. The sleeper usually remains in deep sleep stage N3 for about 20 or 30 minutes. During the next 20 or 30 minutes, the sleeper moves back to slow-wave stage N3, and then stage N2. The first REM sleep lasts for about 5 to 30 minutes. As the night progresses, REM sleep periods increase in duration and deep sleep (stage N3) decreases. If awakened during any stage, the sleeper must return to stage N1 sleep and proceed through all the stages. By morning, the majority of sleep is spent in stages N1, N2, and REM.

FIGURE 17-10 Normal sleep cycle. The sleeper progresses through stages N1, N2, and N3; followed by a return to stage N2. From stage N2 the sleeper moves into REM sleep. The end of REM sleep ends the first sleep cycle. From REM sleep, the sleeper moves back to stage N2, and a new sleep cycle begins.



Older sleeping adults, in either stage N2 or N3 non-REM sleep, often bypass REM sleep altogether and awaken. Except for the older adult, changes in body position during sleep usually occur 20 to 40 times during the night. One or two awakenings are normal for the young adult. The number and duration of nocturnal awakenings tend to increase with age. The duration of non-REM and REM sleep varies with age. Figure 17–11 illustrates the normal sleep cycles of children, young adults, and older adults.

Functions of Sleep

In spite of the fact that sleep is essential for survival—right alongside food and water—the precise function of sleep is still unknown. Once considered a passive, dormant part of our daily lives, it is now known that the brain is very active during sleep. For example, during sleep, the cortical activity is depressed, but the brainstem continues to control such functions as respiration, heart rate, and blood pressure.

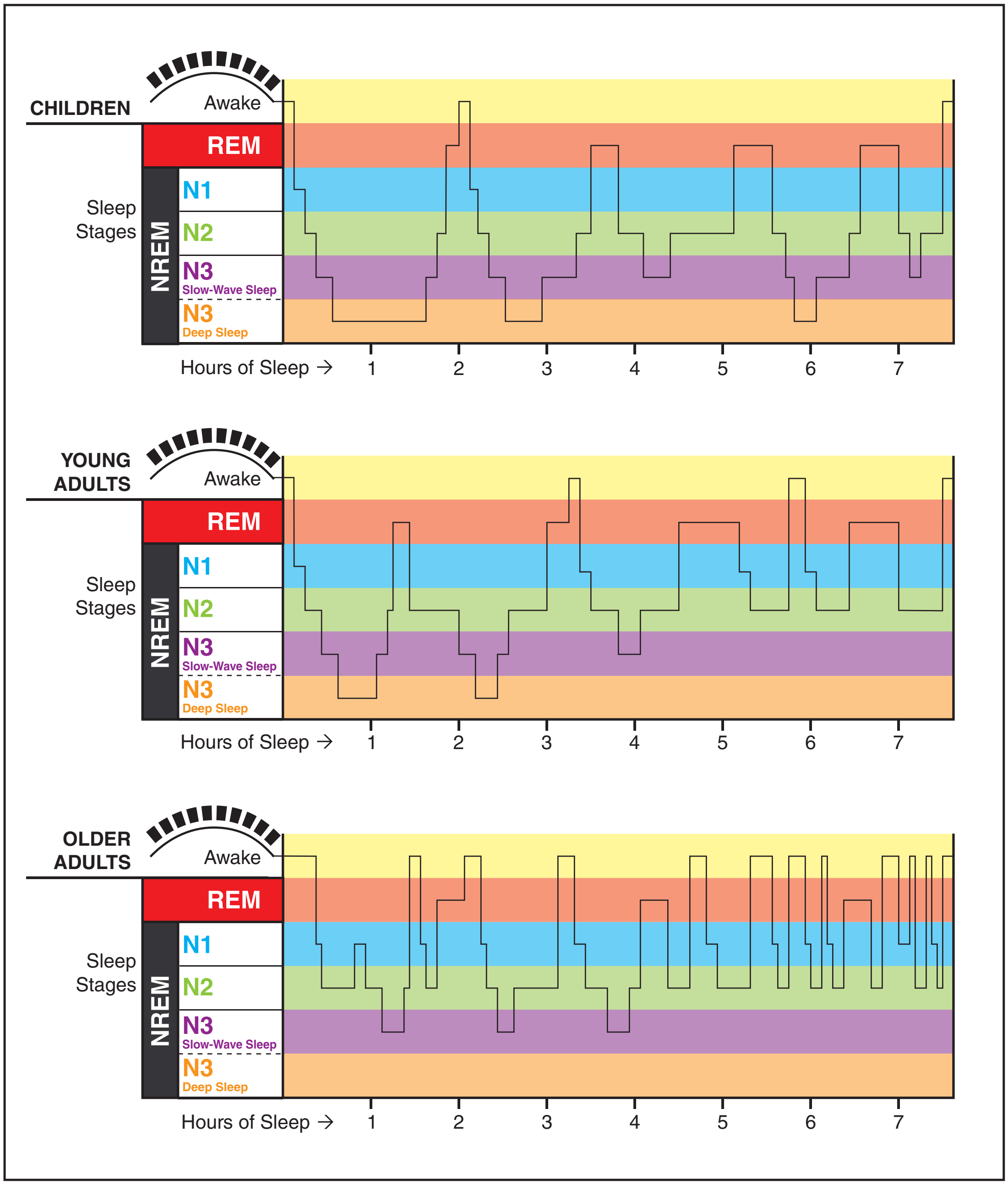
In addition, the lack of sleep has adverse effects on our physical and mental health in numerous ways that are just now beginning to be understood. For example, too little sleep leaves the individual drowsy and unable to concentrate. It also leads to impaired memory and physical performance and reduced ability to carry out basic mental functions. Extreme sleep deprivation can lead to depression, paranoia, hallucinations, and mood swings.

The two most widely accepted theories regarding the purpose of sleep are *restoration* and *energy conservation.*

Restoration

The most widely accepted theory of sleep function is that it provides the body with a period for **restoration** and recuperation. It is thought that non-REM, slow-wave sleep promotes physical growth and healing. This theory is further supported by the fact that slow-wave sleep coincides with the release of growth hormone

FIGURE 17-11 Normal sleep cycles of children, young adults, and older adults.



in children and young adults. Furthermore, many of the body's cells also show increased production and reduced breakdown of proteins during deep sleep. REM sleep appears to play an important role in the restoration of the brain processes, such as attention span, learning and memory, emotional healing, and performing basic social skills.

Energy Conservation

Some suggest that sleep is an extension of homeostasis. In other words, the increased energy used during wakeful hours must be offset by the decreased energy consumed while asleep. This is based, in part, by the fact that the metabolic rate decreases 5 to 25 percent during non-REM, slow-wave sleep. The **energy**

conservation theory is further supported by the fact that slow-wave sleep declines with age; that is, as the energy requirements decrease with age, the need to conserve energy also decreases. It is believed that the decreased need to conserve energy is directly reflected in the decreased slow-wave sleep seen in the older adult.

Circadian Rhythms

Biologic rhythms that occur at regular intervals of about 24 hours are called **circadian rhythms**. Examples of biorhythms include the sleep–wake cycles, changes in cortisol levels, and body temperature fluctuations. When an individual's biologic clock corresponds to a good sleep–wake pattern, the person is said to be in **circadian synchronization**. In other words, the person is asleep when his or her physiologic and psychologic rhythms are at their lowest level and awake when his or her physiologic and psychologic rhythms are at their highest level.

In fact, current publications that deal with many public policy and safety issues involving sleep, sleep deprivation, and sleep disorders strongly suggest that the number-one sleep-related problem affecting most people today is **sleep debt**. Sleep debt is based on the assumption that each person has a specific sleep requirement, an amount that must be obtained each night to maintain constant functioning. All amounts less than this specific sleep requirement constitute lost sleep, and the size of an individual's sleep debt is the total of all nights of lost sleep. A discussion of the relationship of circadian synchronization and normal sleep patterns throughout the average life span follows.

Normal Sleep Patterns

Sleep patterns are well established in the first few months of life and continue throughout life. With advancing age, regular sleep patterns gradually decrease. In general, the well-rested person awakens feeling refreshed, mentally alert, energized, and ready to meet the daily challenges of life. However, the normal sleep–wake pattern (circadian rhythm) varies significantly throughout life.

Newborns and Infants

The **newborn** sleeps about 16 to 17 hours a day. However, this total sleep time is usually divided into about seven fairly equal sleep periods throughout the day and night. Initially, the infant usually awakens every 3 or 4 hours, eats, and then goes back to sleep. About 50 percent of the sleep period is spent in non-REM (stages N1, N2, and N3), and about 50 percent is spent in REM. During the REM periods, the infant commonly exhibits a lot of activity, such as twitching movements, gurgles, and coughing. By 4 months, most infants sleep through the night and take short naps throughout the day. At the end of 1 year, most infants sleep about 14 hours a day and take one or two naps during daylight hours.

Toddlers and Preschoolers

Total sleep time declines from about 14 hours a day at age 2 to about 12 hours a day by the fifth year—primarily due to the elimination of the afternoon nap. Most **preschoolers** still need an afternoon nap. Getting the child to sleep, however, is a frequently reported problem. REM sleep decreases to about 30 percent. Slow-wave sleep is also high.

Children and Adolescents

School-age children sleep between 8 and 12 hours a day. As the child approaches 12 years of age, less sleep is usually required. About 20 percent is spent in REM sleep. Most **adolescents** need between 8 and 10 hours of sleep. About 20 percent is spent in REM sleep.

Young and Older Adults

The **young adult** usually requires between 6 and 8 hours of sleep a day. About 20 percent is spent in REM sleep. Stage N3 progressively decreases during this age, and the number of arousals from sleep increases. The **older adult** needs between 6 and 8 hours of sleep a day. About 20 to 25 percent is spent in REM sleep. Stage N3 is significantly reduced or absent. Older adults frequently require longer periods of time to fall asleep, awaken more frequently, take longer to fall back to sleep, often feel drowsy during the daytime, and take longer to adjust to changes in schedules.

Factors Affecting Sleep

A number of factors affect both the quality (i.e., appropriate amounts of REM and non-REM sleep) and the total time an individual sleeps. Table 17–3 provides an overview of factors affecting sleep.

TABLE 17-3 Factors Affecting Sleep

Age	Age is one of the most important factors affecting sleep.
Illness	Illnesses that cause pain and physical stress can disrupt sleep. Respiratory problems can disrupt a person's sleep. Elevated temperatures can cause reduction in stage N3 sleep and REM sleep.
Environment	The environment can either enhance or hinder sleep. For example, a sudden noise change or light change in the environment can disrupt sleep. Too much or too little ventilation can affect sleep. Too warm or too cold environments can also affect sleep.
Fatigue	Moderate fatigue promotes restful sleep. The more fatigued an individual is, the shorter the first periods of REM sleep. As the sleeper becomes more rested, the REM sleep increases in duration.
Lifestyle	Frequent work shift changes (e.g., nights vs. days) disrupt sleep. Moderate exercise enhances sleep, whereas excessive exercise can delay sleep.
Emotional stress	Anxiety and depression can disrupt sleep.
Alcohol and stimulants	Excessive alcohol often disrupts sleep and may cause nightmares. Caffeine beverages stimulate the central nervous system and, thus, can interfere with sleep.
Diet	Both weight loss and weight gain are felt to affect sleep. Weight loss is usually associated with decreased sleep time, more arousals, and earlier awakenings. Weight gain is associated with an increased total sleep time, fewer arousals, and later awakenings.
Smoking	Smokers usually have more difficulty falling asleep, are easily aroused, and often describe themselves as light sleepers. This is thought to be due to the stimulating effects of nicotine.
Motivation	Fatigue can often be overcome when a person desires to remain awake (e.g., a tired person watching a basketball game). However, when an individual is bored and unmotivated to stay awake, sleep usually rapidly ensues.
Medications	Hypnotics disrupt stage N3, NREM sleep and suppress REM sleep. Beta-blockers may cause insomnia and nightmares. Narcotics suppress REM sleep and cause frequent arousals and drowsiness. Tranquilizers disrupt REM sleep.

Common Sleep Disorders

A basic understanding of common sleep disorders helps the health care practitioner gather and assess important clinical information. Sleep-related problems play an important role in a number of human disorders. For example, problems like an asthma attack tend to occur more often during the night and early morning, perhaps because of changes in hormones, heart rate, medication effect run-out, and other characteristics observed during sleep. The most common sleep disorders include insomnia, hypersomnia, narcolepsy, sleep apnea, periodic limb movement disorder (PLMD), and restless legs syndrome (RLS).

Insomnia

Insomnia is the most common sleep disorder. It is characterized by the inability to fall asleep or to remain asleep. It has been recently said that Americans are in the midst of an "insomnia epidemic"! Insomnia is classified as **transient insomnia** (lasting less than a week), **short-term insomnia** (lasting 1 to 3 weeks), or **chronic insomnia** (lasting longer than 3 weeks). Almost everyone suffers from transient insomnia at one time or another. Common causes of insomnia include changes in sleep environment, unpleasant room temperature, excessive noise, stressful events, jet lag, acute medical or surgical illnesses, ingestion of stimulant medications, and diet. Current research indicates that many insomniacs are hypermetabolic. Insomnia tends to increase with age and affects more women than men. Recent evidence suggests that hospitalized patients are generally sleep deprived, and many institutions are becoming involved in the "Quiet Hospital" noise abatement movement.

Hypersomnia

Hypersomnia is defined as periods of deep, long sleep, or sleep of excessive depth or abnormal duration. It is commonly caused by psychological rather than physical factors. The individual with hypersomnia is often described as being in a state of confusion on awakening or as having extreme drowsiness associated with lethargy. The differential diagnosis of hypersomnia includes sleep apnea, self-imposed sleep restriction, medication effects, periodic limb movement disorders, and circadian rhythm disorders.

Narcolepsy

Narcolepsy is a hereditary disorder characterized by sudden "sleep attacks" that often occur several times a day. The attacks last from several seconds to more than 30 minutes. Narcolepsy is classified as a hypersomnia. Individuals with narcolepsy may also experience *cataplexy* (loss of muscle tone and paralysis of voluntary muscles triggered by emotion), temporary paralysis when they awaken, and visual or auditory hallucinations at the onset or offset of sleep. The symptoms of narcolepsy begin in adolescence or young adulthood and persist throughout life. Nonhereditary narcolepsy symptoms may occur after cerebral trauma, in a condition called *post-traumatic narcolepsy.*

Clinical Connection 17-3

Clinical Signs and Symptoms of Obstructive Sleep Apnea

- Loud snoring, snorting, nocturnal choking
- Observed episodes of breathing cessation during sleep (>20 seconds long)
- Abrupt awakenings accompanied by shortness of breath
- Difficulty staying asleep (insomnia)
- Awakening with a dry mouth, sore throat, or headache
- Nausea
- Excessive daytime sleepiness (hypersomnia)
- Intellectual and personality changes, forgetfulness
- Moodiness, irritability, depression
- Nocturnal enuresis
- Sexual impotence

Sleep Apnea

Sleep apnea is a sleep disorder characterized by the temporary cessation or absence of breathing during sleep. Based on analyses of breathing patterns, the following three types of sleep apnea have been identified: obstructive sleep apnea, central sleep apnea, and mixed sleep apnea.

Obstructive sleep apnea is defined as the cessation of airflow through the nose and mouth with the persistence of diaphragmatic and intercostal muscle activities. Obstructive sleep apnea is the most common of the apneic syndromes, affecting about 4 percent of men and 2 percent of women in the United States. During an episode of obstructive sleep apnea, the sleeper attempts to inhale during a period in which the upper airway muscle tone is momentarily reduced or absent. The negative pressure generated during inspiration causes the pharynx to narrow and the tongue to be sucked back into the oropharygeal area.

The obstructive sleep apnea episode is characterized by loud snoring, followed by silence, during which the sleeper struggles to breathe against an obstructed airway. As the oxygen level falls, the sleeper works even harder to inhale, which in turn increases the upper airway negative pressure and further augments the airway obstruction. Often, the apneic episode ends only after an intense struggle, followed by a loud snorting. The sleeper then resumes snoring. In severe cases, the sleeper may suddenly awaken, sit up in bed, and gasp for air. This cycle may be repeated hundreds of times a night.

The frequent and intense struggles to breathe leave the person sleepy, irritable, or depressed during the day. In addition, because of the low oxygen concentrations associated with each apnea episode, the patient with sleep apnea is more likely to have morning headaches, a loss of interest in sex, a decline in mental (cognitive) function, high blood pressure, irregular heart rhythms, about two times the incidence of heart attacks, and two to three times the frequency of strokes. The obstructive sleep apnea patient is seven times more likely to have an automobile accident than the general population. In severe cases, obstructive sleep apnea may even lead to sudden death from respiratory failure during sleep. The incidence of sleep apnea in patients with strokes is between 60 and 80 percent.

Central sleep apnea is characterized by the cessation of airflow with *no* respiratory efforts; that is, both the diaphragmatic and intercostal muscle activities are absent.

Mixed sleep apnea is characterized by an initial cessation of airflow with no respiratory effort (central apnea), followed by a period of upper airway obstruction (obstructive apnea).

It is estimated that approximately 18 million people in the United States have sleep apnea. However, most have not had the problem diagnosed. Common characteristics of sleep apnea include loud snoring, obesity, and excessive daytime sleepiness and fatigue. The disorder can easily be diagnosed at a sleep center that performs polysomnography. If sleep apnea is diagnosed, several treatments are available based on the type of sleep apnea the patient demonstrates.

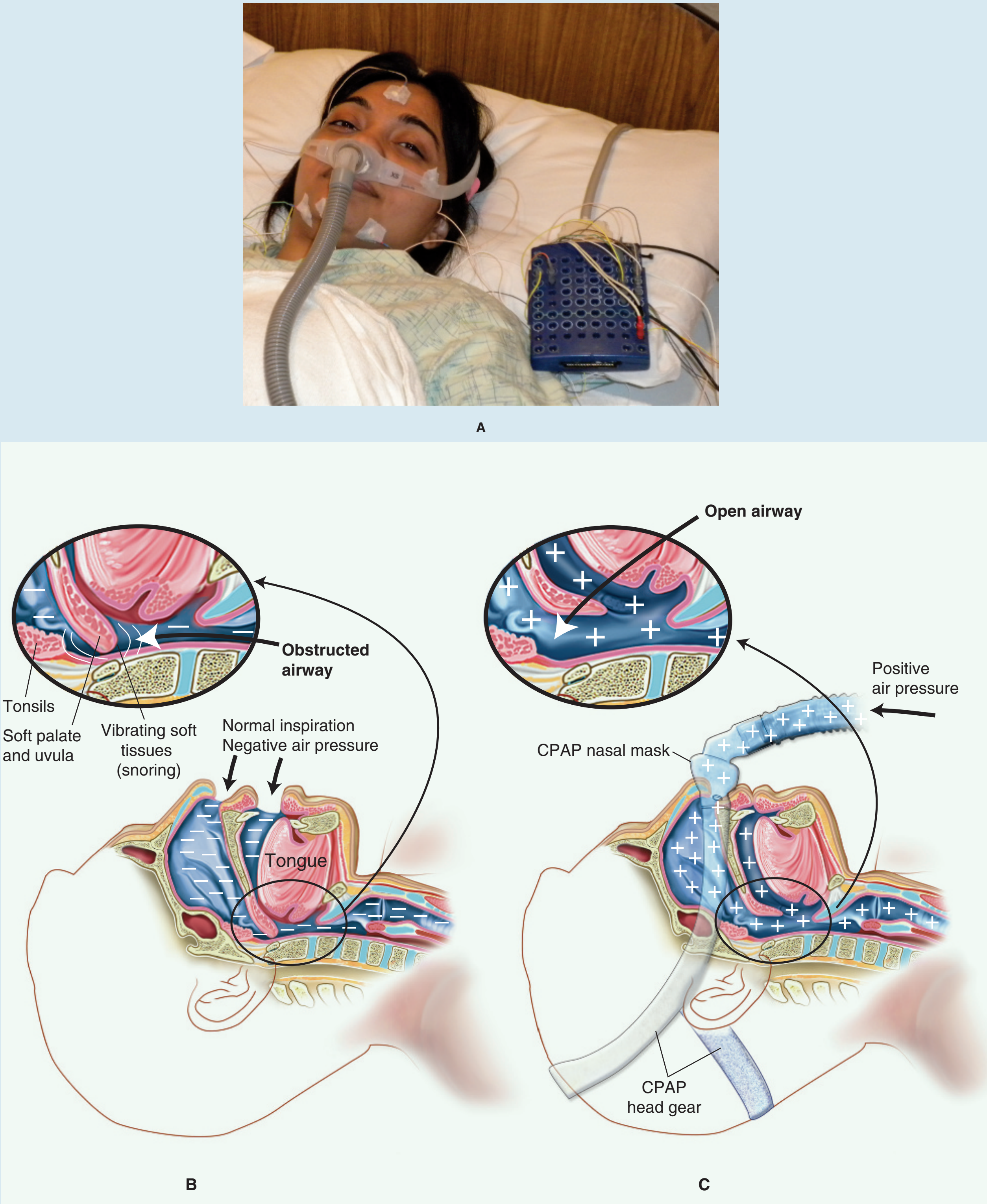
Clinical Connection 17-4

Therapeutic Effects of Continuous Positive Airway Pressure (CPAP) in Obstructive Sleep Apnea

The most common—and arguably the most effective—treatment for obstructive sleep apnea (OSA) is the use of a continuous positive airway pressure (CPAP) device. Nocturnal CPAP therapy is useful in preventing the collapse of the airway and is the standard treatment for most cases of OSA. CPAP is not indicated in pure central sleep apnea (Figure 17–12).

Clinical Connection 17-4, Continued

FIGURE 17-12 **A.** A patient on CPAP during a sleep study. **B.** An obstructive airway during inspiration. **C.** The therapeutic effects of positive pressure from a CPAP mask preventing airway obstruction.


A
Obstructed airway
Tonsils
Soft palate and uvula
Vibrating soft tissues (snoring)
Normal inspiration
Negative air pressure
Tongue
B
Open airway
Positive air pressure
CPAP nasal mask
CPAP head gear
C

Clinical Connection 17-5

Risk Factors Associated with Obstructive Sleep Apnea

- Male gender
- Excessive weight (obesity)
- Increasing age (especially older than 65)
- Large neck size (in males, >17 inches in circumference)
- Hypertension
- Hypothyroidism
- Anatomic narrowing of upper airway (e.g., enlarged tonsils or adenoids)
- Chronic nasal congestion
- Diabetes
- Postmenopausal state
- Craniofacial abnormalities (e.g., retrognathia, Down's syndrome)
- Family history of sleep apnea
- Race (Blacks, Hispanics, and Pacific Islanders more at risk than Caucasians)
- Alcohol, sedatives, or tranquilizers
- Smoking

Clinical Connection 17-6

Risk Factors Associated with Central Sleep Apnea

- Male sex—males are more likely than females to develop central sleep apnea.
- Age—people over 65 years of age have a higher risk of central sleep apnea, especially if other risk factors are present.
- Heart disorders—individuals with atrial fibrillation or congestive heart failure are at more risk of central sleep apnea.
- Stroke or brain tumor—either can impair the brain's ability to regulate breathing.
- High altitude—sleeping at a higher altitude than a person is accustomed to can increase the risk of central sleep apnea.
- Opioids—morphine, oxycodone, and codeine are associated with central sleep apnea.

Periodic Limb Movement Disorder

Periodic limb movement disorder (PLMD) is characterized by repetitive stereotyped movements of the leg muscles during sleep with a rhythmic pattern occurring about 30 seconds apart. PLMD occurs during non-REM sleep and usually stops when the patient awakens. Because the patient is not aware of the problem, the disorder is usually first reported by a family member. The incidence of PLMD increases with age. PLMD is often seen in patients with *restless legs syndrome*.

Clinical Connection 17-7

Management of Sleep Apnea

It is now known that many pathologic conditions are associated with sleep apnea, including hypoxemia, fragmented sleep, cardiac dysrhythmias, and neurologic and psychiatric disorders. In general, the prognosis is more favorable for obstructive and mixed apnea than for central sleep apnea. The following provides an overview of the common therapeutic strategies used for obstructive and central sleep apnea and their effectiveness:

Clinical Connection 17-7, Continued

Common Therapeutic Modalities for Obstructive Sleep Apnea and Central Sleep Apnea

	Types of Apnea	
Therapy	**Obstructive Sleep Apnea**	**Central Sleep Apnea**
Mechanical ventilation		
• Continuous positive airway pressure (CPAP)	Therapeutic (100%)	Only fairly effective
• Mechanical ventilation	Short-term	Short-term
• Negative-pressure ventilation	Contraindicated	Therapeutic
• Adaptive servo-ventilation (variable positive airway pressure [VPAP])	Not indicated	Therapeutic
Oxygen therapy	Rarely therapeutic, but is used in addition to CPAP in severe cases	Sometimes therapeutic
Surgical		
• Tracheostomy	Therapeutic (100%)	Not indicated
• Palatopharyngoplasty	Occasionally therapeutic	Not indicated
• Mandibular advancement	Occasionally therapeutic	Not indicated
Medical devices (e.g., mandibular advancement devices)	Indicated if properly fitted	Not indicated
Phrenic nerve pacemaker	Not indicated	Experimental

Restless Legs Syndrome

Restless legs syndrome (RLS) is characterized as intense unpleasant feelings described as crawling, prickling, tingling, burning, painful, aching, cramping, knifelike, or itching sensations. These crawling sensations occur mostly between the knees and ankles, causing a strong urge to move the legs to relieve the feelings. Motor restlessness is noted mostly in the legs but is occasionally reported in the arms.

RLS is emerging as one of the most common sleep disorders. Although it may occur at any age, it is most common among the elderly. Iron deficiency anemia is often present. The disorder causes a constant leg movement during the day and insomnia during the night. RLS may be exacerbated during pregnancy or by caffeine, diabetes, or renal insufficiency.

Normal Cardiopulmonary Physiology during Sleep

In spite of the fact that the complete purpose of sleep is not known, a significant amount of scientific knowledge is known about the physiologic differences between wakefulness periods and sleep periods. The following provides an overview of important physiologic changes that normally occur during sleep.

Autonomic Nervous System

In general, parasympathetic activity increases at sleep onset and continues throughout non-REM sleep. The parasympathetic tone continues to increase during the transition to REM sleep. This increased parasympathetic activity causes a number of autonomic nervous system changes throughout several areas of the body, including the musculoskeletal system, thermal regulation, renal function, genital function, gastrointestinal function, endocrine function, cardiovascular function, sleep-related dysrhythmias, cerebral blood flow, and respiratory physiology.

Musculoskeletal System

The somatic skeletal muscles usually have their highest muscle tone during the wakeful state. The muscle tone decreases with sleep onset and throughout non-REM sleep. Muscle tone is at its lowest level during REM sleep. During REM sleep, neural impulses to most skeletal muscles stop, and a lack of muscle tone ensues. In essence, the sleeper is temporarily paralyzed. This is especially true for the muscles of the back, neck, arms, and legs and the posterior muscles of the pharynx, including the **genioglossus muscle** (which normally pulls the tongue down and forward), the **infrahyoid muscle group**, and the **palatal muscle group**. The partial paralysis may allow the tongue to fall back into the oral pharyngeal area during inspiration (i.e., negative-pressure phase). In severe cases, this condition can lead to obstructive sleep apnea.

Less affected are the muscles that move the eyes and the diaphragm. This explains, in part, why the sleeper does not physically act out a vivid dream during REM sleep—such as running from someone or swinging at a baseball. Instead, the sleeper only twitches or makes small movements. Sleepers with a malfunctioning REM system, on the other hand, thrash around in their sleep, oftentimes hitting their spouse or hurting themselves as they act out a dream (the so-called REM behavior disorder).

Thermal Regulation

The body temperature usually falls by 1°C to 2°C during non-REM sleep. During REM sleep, the body temperature tends to increase with cyclic variability.

Renal Function

Renal perfusion is decreased during non-REM sleep, resulting in decreased urine production. In addition, water reabsorption increases during non-REM sleep, causing a decrease in urine production. Urine production decreases even more during REM sleep.

Genital Function

There are few or no changes in the genital function during non-REM sleep. In men, REM sleep is associated with penile tumescence (erection). The erection usually occurs at the start of REM sleep and continues throughout the REM sleep phase. In most cases, the erection is lost at the end of REM sleep. Similar genital changes occur in the erectile tissue of women during REM sleep. The sleep-related erections develop as a result of the increased parasympathetic activity and local vasodilation that normally occurs during REM sleep.

Gastrointestinal Function

The effects of sleep on the gastrointestinal system are mainly caused by an increased parasympathetic activity, circadian rhythm factors, and central nervous system activity. During sleep, salivation and esophageal motility (swallowing) are markedly decreased. Gastric acid secretion follows a circadian rhythm, with the peak acid production occurring between 10:00 P.M. and 2:00 A.M. This circadian pattern is mediated by the vagus nerve. Colonic function is also decreased during sleep, which in turn results in a reduced colonic motility. When awakened in the morning, the colonic motility increases significantly.

Endocrine Function

Plasma growth hormone concentrations usually peak about 90 minutes after the onset of sleep, typically during stage N3. Patients with obstructive sleep apnea or narcolepsy commonly have a decreased correlation between sleep and growth hormone concentration. Adrenocorticotropic hormone (ACTH) and cortisol secretions follow a circadian pattern, which typically peaks during delta sleep (stage N3) between 4:00 A.M. and 8:00 A.M.

Cardiovascular Function

During non-REM sleep, the vagal nerve function provides relative autonomic stability. The heart rate and blood pressure variations during non-REM sleep follow a sinusoidal pattern—called "nocturnal dipping." That is, during a normal inspiration, the heart rate and blood pressure increase briefly in order to accommodate venous return and increased cardiac output. During expiration, the heart rate and blood pressure gradually decrease. This normal cardiovascular rhythm unevenness is a positive marker for good cardiac health. Its absence is associated with increased age, abnormal vagus nerve function, or heart pathology. During REM sleep, the heart rate becomes variable with episodes of both increased and decreased rates. The heart rate may increase as much as 35 percent during REM sleep.

Sleep-Related Dysrhythmias

During non-REM sleep, there is an increased activity of the vagal nerve— which causes a decreased heart rate, blood pressure, and cardiac metabolism. Collectively, these activities reduce the sleeper's risk for cardiac dysrhythmia. However, the decreased blood pressure during non-REM sleep may lead to myocardial hypoperfusion. On the other hand, the surge of autonomic activity during REM sleep increases the heart rate and blood pressure and increases the risk for heart dysrhythmias. Premature ventricular contractions (PVCs), paroxysmal atrial tachycardia, atrial fibrillation, nonsustained ventricular tachycardia, and even periods of cardiac asystole may be seen. In addition, the increased sympathetic activity during REM sleep results in a reduced oxygen supply-to-demand ratio, coronary vasoconstriction, and variation of both cardiac ventricular preload and afterload. Nocturnal angina (chest pain) is sometimes seen in patients with sleep apnea, as is orthopnea and paroxysmal nocturnal dyspnea, reflecting congestive heart failure.

Cerebral Blood Flow

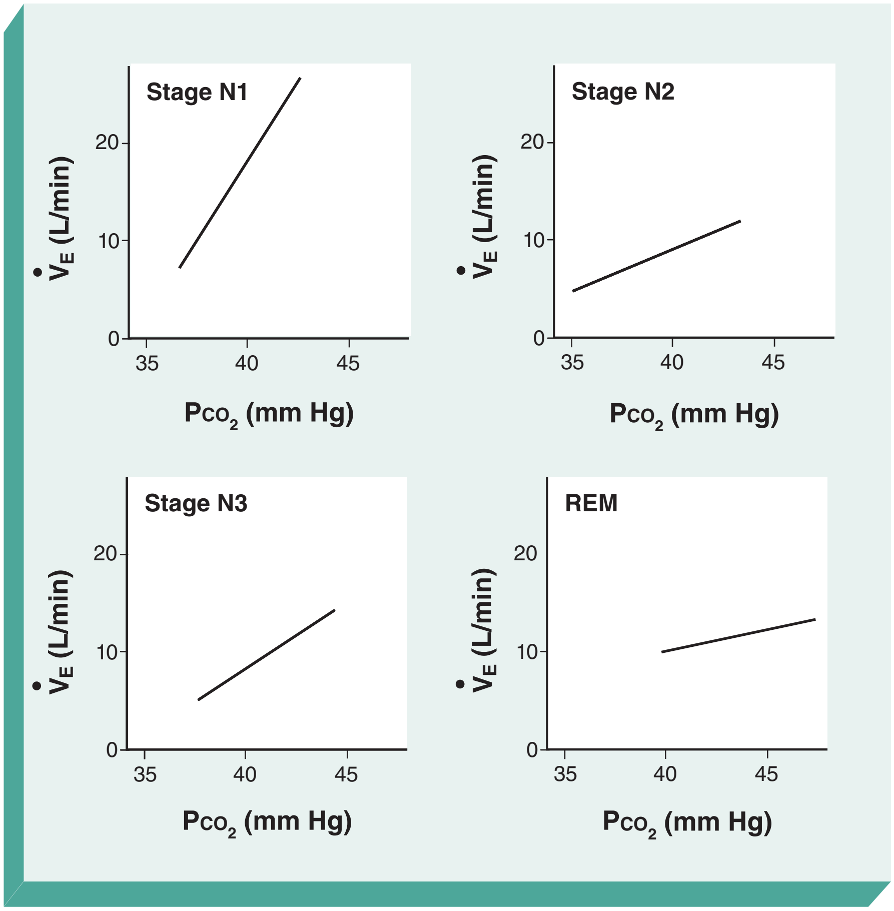
During non-REM sleep, cerebral blood flow decreases. During REM sleep, cerebral blood flow increases. Spinal cord blood flow also increases during REM sleep. In addition, the cerebral blood flow is decreased during postsleep wakefulness when compared to presleep wakefulness. The cerebral metabolic rate increases during REM sleep.

Respiratory Physiology

As discussed in Chapter 9, the intrinsic rhythmicity of ventilation is coordinated by the medulla oblongata, which responds to neural impulses generated from the oxygen (P_{O_2})-sensitive peripheral chemoreceptors (located in the aorta and carotid arteries) and the carbon dioxide (P_{CO_2}) or H^+-sensitive central chemoreceptors (located in the medulla). The primary function of ventilation, therefore, is to maintain the P_{O_2} and P_{CO_2} within normal physiologic boundaries.

Although the precise mechanism is not known, the medulla's ability to respond to P_{O_2} and P_{CO_2} changes is reduced during non-REM sleep. This is especially true in regard to the medulla's ability to react to sudden changes in the P_{CO_2} level. In non-REM sleep, the respiratory rate decreases, causing the minute ventilation to fall as much as 0.5 to 1.5 L/min. It is suggested that the reduced minute ventilation is caused, in part, by (1) the decreased metabolic rate that occurs during sleep, (2) the reduced ability for the medulla to respond to ventilatory signals during sleep, (3) the decreased sensitivity of the P_{O_2} and P_{CO_2} chemoreceptors to send signals to the medulla during sleep, and (4) the increased airway resistance caused by reduced muscle tone in the upper airway. Figure 17–13 illustrates the normal ventilatory response to changing P_{CO_2} levels during non-REM and REM sleep. During REM sleep, the respiratory rate increases and decreases irregularly. This irregular respiratory pattern is thought to be secondary to brainstem respiratory neuron activity.

FIGURE 17-13 Normal ventilatory response to changing P_{CO_2} level during non-REM and REM sleep.



Clinical Connection 17-8

Case Study—Role of the Respiratory Therapist in Caring for the Obstructive Sleep Apnea Patient

In the Clinical Application Case 1 (page 543), the respiratory therapist is called to care for a 65-year-old man with obstructive sleep apnea. This case illustrates how patients with acute transient ischemic attacks and minor strokes are ideal candidates for CPAP therapy—especially if other comorbidities such as obesity can be addressed. The role of the respiratory therapist in this case can be seen in the (1) initial assessment of the patient in the Emergency Department, (2) instructing the patient for his polysomnogram in the Sleep Disorders Center, and (3) the continued involvement in education of the patient and CPAP compliance monitoring once the patient was discharged.

Chapter Summary

Sleep is a naturally occurring state of partial unconsciousness. The two major types of sleep are non-rapid-eye-movement sleep (non-REM sleep or NREM sleep) and rapid-eye-movement sleep (REM sleep). Non-REM sleep consists of stages N1 and N2, which are described as light-sleep stages, and stage N3 is referred to as deep sleep or slow-wave sleep stages. REM sleep resembles wakefulness on the EEG and is the period in which most dreaming occurs and when there is temporary paralysis of most of the skeletal muscles. One full sleep cycle begins with stage N1 and progresses through stages N2 and N3, followed by a return to stage N2. From stage N2, the sleeper moves into REM sleep. The conclusion of REM sleep ends the first sleep cycle. Between four and six full sleep cycles occur during a normal night's sleep.

The two most accepted theories regarding the purpose of sleep are restoration and energy conservation. Biologic rhythms that occur at regular intervals of 24 hours are called circadian rhythms. When an individual's biologic clock corresponds to a good sleep–wake pattern, the person is said to be in circadian synchronization. Sleep patterns are well established in the first few months of life and continue throughout life. With advancing age, regular sleep patterns gradually decrease.

Numerous facts affect both the quality of and the total time an individual sleeps. Such factors include age, illness, environment, fatigue, lifestyle, emotional stress, alcohol and stimulants, diet, smoking, motivation, and medications. Common sleep disorders include insomnia, hypersomnia, narcolepsy, sleep apnea, periodic limb movement disorder, and restless legs syndrome. Although not fully understood, a considerable amount of information is known regarding the differences in physiology during wakefulness and sleep. Such differences include those affecting the autonomic nervous system, musculoskeletal system, thermal regulation, renal function, genital function, gastrointestinal function, endocrine function, cardiovascular function, sleep-related dysrhythmias, cerebral blood flow, and respiratory physiology.

Clinical connections associated with these topics include (1) the sleep disorder specialist—trends, education, and certification, (2) types of sleep studies, (3) clinical signs and symptoms associated with obstructive sleep apnea, (4) the therapeutic effects of continuous positive airway pressure (CPAP) in obstructive sleep apnea, (5) risk factors associated with obstructive sleep apnea, (6) risk factors associated with central sleep apnea, (7) management of sleep apnea, and (8) a case study discussing the role of the respiratory therapist in caring for the obstructive sleep apnea patient.

1 Clinical Application Case

A 65-year-old man with a long history of insulin-dependent diabetes mellitus, hypertension, and a recent transient ischemic attack (TIA) came to the hospital Emergency Department with a history of slurred speech, left-sided weakness, and increasing somnolence. The respiratory therapist who first saw him found the following sleep history: the man got into bed around 11:00 P.M.; woke frequently during the night with gasping, choking, and snorting; and woke at 6:00 A.M. not feeling refreshed. His bed partner stated that he snored loudly and that he stopped breathing in his sleep many times each night. It was further noted that these events had gotten worse since the patient's TIAs.

His medications were aspirin (325 mg daily), metformin, and lisinopril. He did not smoke, abuse alcohol, or use caffeine. He was retired from work as an insurance executive. He fell asleep during the day when reading or watching television but denied any sleep-related automobile accidents.

Physical examination revealed the following: height 5 ft 8 in., weight 240 lb, BMI = 36. Temperature 98.8°F, pulse 84, blood pressure 146/90, respiratory rate 16, Sp_{O_2} on room air awake 96 percent. HEENT examination (head, ears, eyes, nose, and throat) showed a class IV Mallampati configuration, with a low-lying soft palate, large uvula, and widened tonsillar pillars. There was "scalloping" of the edges of the tongue,

(*continued*)

Clinical Application Case 1 (continued)

suggesting an element of macroglossia. His neck circumference was 18 inches, and he was very jowly. Examination of his heart, lungs, and abdomen was normal. There was 2+ bilateral leg edema. Neurological examination showed mild weakness of the left arm and hand but was otherwise normal, except for what appeared to be some short-term memory loss. His Epworth Sleepiness Scale was 20/24.[4]

While the patient was in the Emergency Department, he fell asleep repeatedly and snored loudly. He was placed on a pulse oximeter and was found to frequently desaturate to an Sp_{O_2} of less than 75 percent. He was easily aroused, and a CT scan of the head was normal. He was discharged, and an outpatient nocturnal polysomnogram was scheduled for a few days later.

The polysomnogram was performed in the hospital's Sleep Disorders Center, where a respiratory therapist assisted in the initial setup and monitoring. The study showed that he had an Apnea-Hypopnea Index of 56 episodes per hour (normal $\leq$ 5/hr). The longest episode was 62 seconds long, and there were cyclical oxygen desaturations to a low 70 percent. All the events were obstructive in nature.

Once these results were known, a CPAP titration study was done the following night. This study showed that a CPAP pressure of 8.0 cm H_2O reduced the apnea-hypopnea index to 2.0/hr, and reduced the nadir—that is, the lowest point—of his oxygen saturation to 92 percent.

The respiratory therapist assisted in obtaining a comfortable CPAP mask for the patient, enrolled him in an AWAKE class for patients with sleep apnea, and monitored him there for CPAP compliance. The patient was also referred to the hospital's weight loss management program and did well thereafter. There had been no recurrence of cardiovascular or neurological events at his scheduled 2-year follow-up.

Discussion

Patients with acute TIA and minor stroke are ideal candidates for prevention of recurrent events—particularly if co-morbidities such as sleep apnea and obesity can be addressed. Long-term studies of the effect of CPAP in this setting are currently in process. The role of the respiratory therapist in this case can be seen in the (1) initial assessment of the patient in the Emergency Department, (2) instructing the patient for his polysomnogram in the Sleep Disorders Center, and (3) the continued involvement in education of the patient and CPAP compliance monitoring once the patient was discharged.

---

[4] The Epworth Sleepiness Scale is an eight-question assessment of daytime sleepiness in which the respondent rates how likely one is to fall asleep in a variety of situations. Scores less than 10 are normal, and scores higher than 10 may suggest the need for additional evaluation by a sleep specialist.

Review Questions

1. Which of the following is also known as paradoxic sleep?

A. Stage N1 non-REM sleep
B. Stage N2 non-REM sleep
C. Stage N3 non-REM sleep
D. Stage W (wake)
E. REM sleep

2. Most sleep study epochs are

A. 10 seconds in duration
B. 20 seconds in duration
C. 30 seconds in duration
D. 60 seconds in duration

3. K complexes first appear in which of the following stages during one full sleep cycle?

A. Stage N1
B. Stage N2
C. Stage N3
D. REM

4. The newborn sleeps about how many total hours during a 24-hour period?

A. 6 to 8 hours
B. 8 to 12 hours
C. 13 to 15 hours
D. 16 to 17 hours

5. Which of the following is the most common sleep disorder?

A. Insomnia
B. Narcolepsy
C. Sleep apnea
D. Restless legs syndrome

6. Which of the following is characterized by prominent alpha waves (>50 percent)?

A. Eyes open—wake
B. Eyes closed—wake
C. Stage N2 non-REM sleep
D. REM sleep

7. Which of the following occupies the greatest proportion of the total sleep time?

A. Stage N1 non-REM sleep
B. Stage N2 non-REM sleep
C. Stage N3 non-REM sleep
D. REM sleep

8. Sleep spindles first appear in which of the following?

A. Stage N1 non-REM sleep
B. Stage N2 non-REM sleep
C. Stage N3 non-REM sleep
D. REM sleep

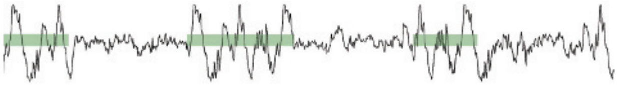
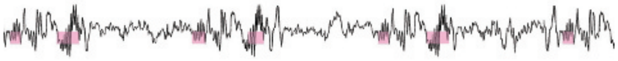
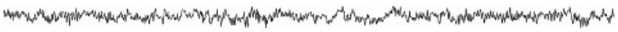
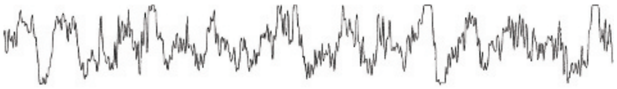
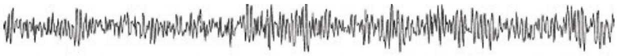
9. Vertex shape waves often appear toward the end of which of the following sleep stages?

A. Stage N1 non-REM sleep
B. Stage N2 non-REM sleep
C. Stage N3 non-REM sleep
D. REM sleep

10. Delta waves are associated with which of the following stages?

1. Stage N1 non-REM sleep
2. Stage N2 non-REM sleep
3. Stage N3 non-REM sleep
4. Stage wake
5. REM sleep
    A. 3 only
    B. 1 and 2 only
    C. 2 and 3 only
    D. 3 and 5 only

Directions: Match the type of waveform listed under column A to the graphic appearance of the waveform shown under column B.

COLUMN A	COLUMN B
1. ___Delta waves	A. 
2. ___Alpha waves	B. 
3. ___K complex	C. 
4. ___Sleep spindles	D. 
5. ___Beta waves	E. 

Clinical Application Questions

1. On the Epworth Sleepiness Scale, scores less than ____________ are normal, and scores higher than ____________ may suggest the need for additional evaluation by a sleep specialist.
2. True ____________ False ____________ Patients with acute TIA and minor stroke are ideal candidates for prevention of recurrent events.
3. True ____________ False ____________ The respiratory care practitioner's role includes CPAP compliance monitoring.

SECTION 3

The Cardiopulmonary System during Unusual Environmental Conditions

CHAPTER 18
Exercise and Its Effects on the Cardiopulmonary System

CHAPTER 19
High Altitude and Its Effects on the Cardiopulmonary System

CHAPTER 20
High-Pressure Environments and Their Effects on the Cardiopulmonary System

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CHAPTER 18

Exercise and Its Effects on the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the effects of exercise on the cardiopulmonary system.
2. Describe the interrelationships among muscle work, oxygen consumption, and cardiac output.
3. Discuss the effect of training on the heart and on cardiac output.
4. Differentiate between stroke volume and heart rate in increasing the cardiac output.
5. Describe how body temperature and cutaneous blood flow relate to a number of symptoms collectively referred to as heat stroke.
6. List the benefits of pulmonary rehabilitation.

Introduction

During heavy exercise, components of the cardiopulmonary system may be stressed close to their limit. Alveolar ventilation may increase as much as 20-fold, oxygen diffusion capacity as much as 3-fold, cardiac output as much as 6-fold, muscle blood flow as much as 25-fold, oxygen consumption as much as 20-fold, and heat production as much as 20-fold.

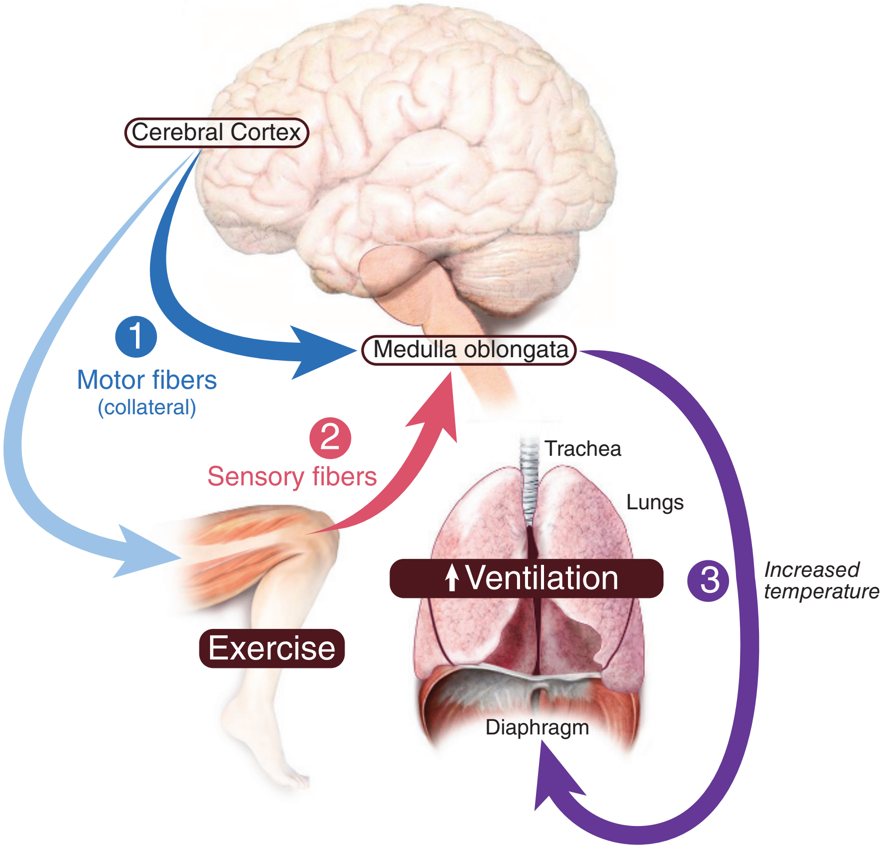
Muscle training can increase muscle size and strength 30 to 60 percent. The efficiency of intracellular metabolism may increase by 30 to 50 percent. The size of the heart chambers and the heart mass in elite athletes, such as marathon runners, may be increased by 40 percent. When the level of exercise is greater, however, than the ability of the cardiopulmonary system to provide a sufficient supply of oxygen to the muscles, anaerobic metabolism ensues. The point at which anaerobic metabolism develops is called the **anaerobic threshold**.

Respiratory Functions

Control of Ventilation

The precise mechanism responsible for increased alveolar ventilation during exercise is not well understood. Exercise causes the body to consume a large amount of oxygen and, simultaneously, to produce a large amount of carbon dioxide. Alveolar ventilation increases so much, however, that the concentration of these gases in the body does not change significantly. In addition, no oxygen or carbon dioxide

FIGURE 18–1 Mechanisms by which exercise stimulates ventilation. **1.** Collateral fibers from the motor neurons travel to the medulla. **2.** Sensory signals from the exercising limbs are sent to the medulla. **3.** The increase in body temperature during exercise may also increase ventilation.



chemoreceptors have been identified on the venous side of circulation, or in the lungs, that could account for the increased alveolar ventilation during exercise. Thus, it is unlikely that the increased ventilation seen in exercise is caused by either of these gases.

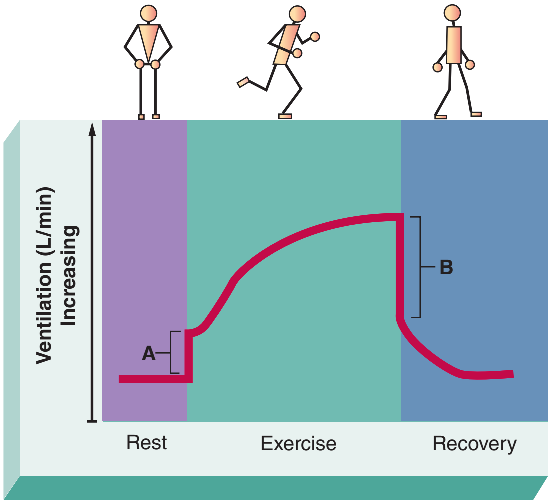
It has been suggested that the increased ventilation is caused by neural impulses sent to the medulla by way of the following pathways (Figure 18–1):

1. The cerebral cortex sending signals to the exercising muscles may also send collateral signals to the medulla oblongata to increase the rate and depth of breathing.
2. Proprioceptors in the moving muscles, tendons, and joints transmit sensory signals via the spinal cord to the respiratory centers of the medulla.
3. The increase in body temperature during exercise also may contribute to increased ventilation.

Alveolar Ventilation

During normal quiet breathing, an adult exchanges about 6 L of gas per minute. During strenuous exercise, this can increase to 120 L/min, a 20-fold increase. Depending on the intensity and duration of the exercise, alveolar ventilation must increase to (1) supply sufficient oxygen to the blood and (2) eliminate the excess carbon dioxide produced by the skeletal muscles. The increased alveolar ventilation is produced mainly by

FIGURE 18–2 The relationship of exercise and ventilation. Note **(A)** the abrupt increase in ventilation at the outset of exercise and **(B)** the even larger, abrupt decrease in ventilation at the end of exercise.



an increased depth of ventilation (increased tidal volume) rather than by an increased rate of ventilation. During very heavy exercise, however, both an increased depth and frequency of ventilation are seen. The tidal volume is usually about 60 percent of the vital capacity, and the respiratory rate may be as high as 30 breaths/min.

Three distinct consecutive breathing patterns are seen during mild and moderate exercise. The **first stage** is characterized by an increase in alveolar ventilation, within seconds after the onset of exercise. The **second stage** is typified by a slow, gradual further increase in alveolar ventilation developing during approximately the first 3 minutes of exercise. Alveolar ventilation during this period increases almost linearly with the amount of work performed. During the **third stage**, alveolar ventilation stabilizes. When an individual stops exercising, alveolar ventilation decreases abruptly (Figure 18–2).

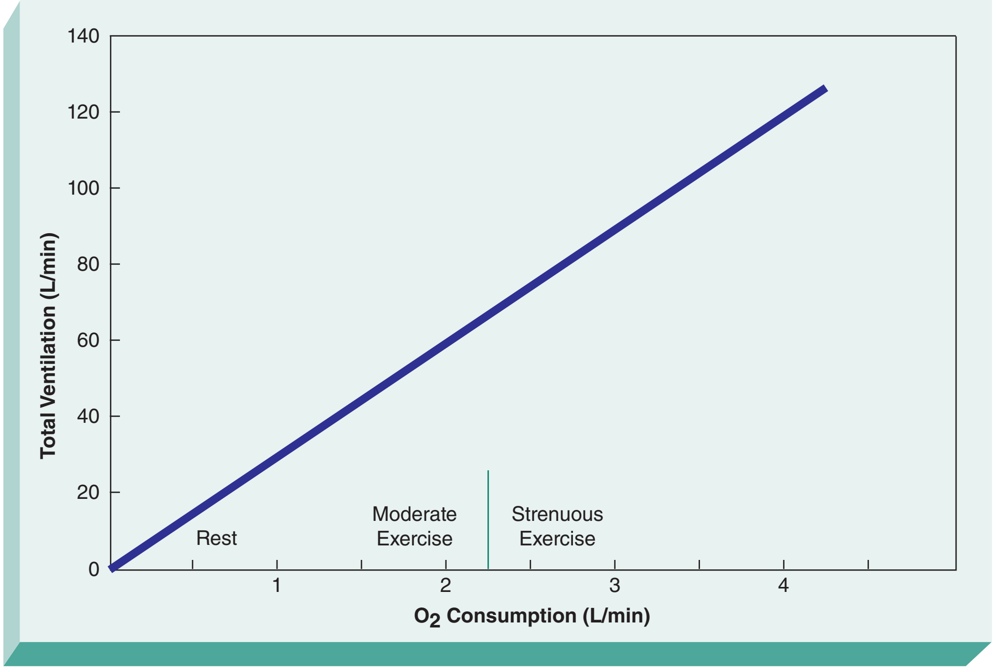
During very heavy exercise, the steady-state third stage may not be seen. In fact, when approximately 60 to 70 percent of the maximal exercise level is reached during the linear second stage, alveolar ventilation increases proportionately more than the oxygen uptake. The additional stimulation is thought to be caused primarily by the accumulation of lactic acids in the blood after the anaerobic threshold has been reached. It is suggested that the H^+ ions generated by the lactic acids stimulate the peripheral chemoreceptors, which in turn send neural impulses to the medulla oblongata to increase alveolar ventilation (refer to Figure 9–8).

The maximum alveolar ventilation generated during heavy exercise under normal conditions is only about 50 to 65 percent of the maximum voluntary ventilation (also called maximum breathing capacity). This provides the athlete with an important reserve of alveolar ventilation, which may be required in such conditions as short bursts of increased exercise, exercise at high altitudes, or exercise during very hot and humid conditions. Because there is normally a large alveolar ventilatory reserve during exercise, it is not the limiting factor in the delivery of oxygen to the muscles during maximal muscular aerobic metabolism. As discussed later, the inability of the heart to pump sufficient blood to the working muscles is the major limiting factor.

Oxygen Consumption

At rest, normal oxygen consumption ($\dot{V}_{O_2}$) is about 250 mL/min. The skeletal muscles account for approximately 35 to 40 percent of the total $\dot{V}_{O_2}$. During exercise, the skeletal muscles may account for more than 95 percent of the $\dot{V}_{O_2}$. During heavy exercise, the $\dot{V}_{O_2}$ of an untrained person may be more than 3500 mL of O_2/min. The $\dot{V}_{O_2}$ of an elite athlete while running a marathon may be over 5000 mL O_2/min. Figure 18–3 shows the linear relationship between $\dot{V}_{O_2}$ and alveolar ventilation exercise intensity increases.

FIGURE 18-3 There is a linear relationship between oxygen consumption ($\dot{V}_{O_2}$) and alveolar ventilation as the intensity of exercise increases. Note that when the anaerobic threshold is reached during strenuous exercise, the linear relationship between $\dot{V}_{O_2}$ and alveolar ventilation will no longer exist. When the anaerobic threshold is reached, there will be an abrupt increase in alveolar ventilation with little or no increase in $\dot{V}_{O_2}$.



Arterial Blood Gas Levels during Exercise

No significant Pa_{O_2}, Pa_{CO_2}, or pH changes are seen between rest and approximately 60 to 70 percent of maximal $\dot{V}_{O_2}$. During very heavy exercise, however, when lactic acidosis is present, both the pH and Pa_{CO_2} decline. Although controversy exists, it is believed that arterial acidosis stimulates the carotid chemoreceptors, causing increased alveolar ventilation and promoting respiratory acid–base compensation. The Pa_{O_2} remains constant during mild, moderate, and heavy exercise (Figure 18–4).

Oxygen Diffusion Capacity

The oxygen diffusion capacity increases linearly in response to the increased oxygen consumption ($\dot{V}_{O_2}$) during exercise (Figure 18–5). The oxygen diffusion capacity may increase as much as 3-fold during maximum exercise. It has been shown that the increased oxygen diffusion capacity results from the increased cardiac output during exercise. The increased cardiac output causes the intravascular pressure in the pulmonary artery and left atrium to increase, which in turn serves to (1) distend the pulmonary capillaries that are not fully dilated and (2) open, or recruit, closed pulmonary capillaries (refer to Figure 5–30). As more blood flows through the lungs, more alveolar-capillary units become available for gas exchange. This provides a greater surface area through which oxygen can diffuse into the pulmonary capillary blood.

Alveolar-Arterial P_{O_2} Difference

Normally, there is a mean alveolar-arterial oxygen tension difference $P_{(A-a)O_2}$ of about 10 mm Hg because of (1) mismatching of ventilation and perfusion and (2) right-to-left pulmonary shunting of blood. Despite increases in oxygen consumption ($\dot{V}_{O_2}$), alveolar ventilation, and cardiac output, the $P_{(A-a)O_2}$ remains essentially

FIGURE 18-4 The effect of oxygen consumption on Pa_{O_2} and Pa_{CO_2} as the intensity of exercise increases.

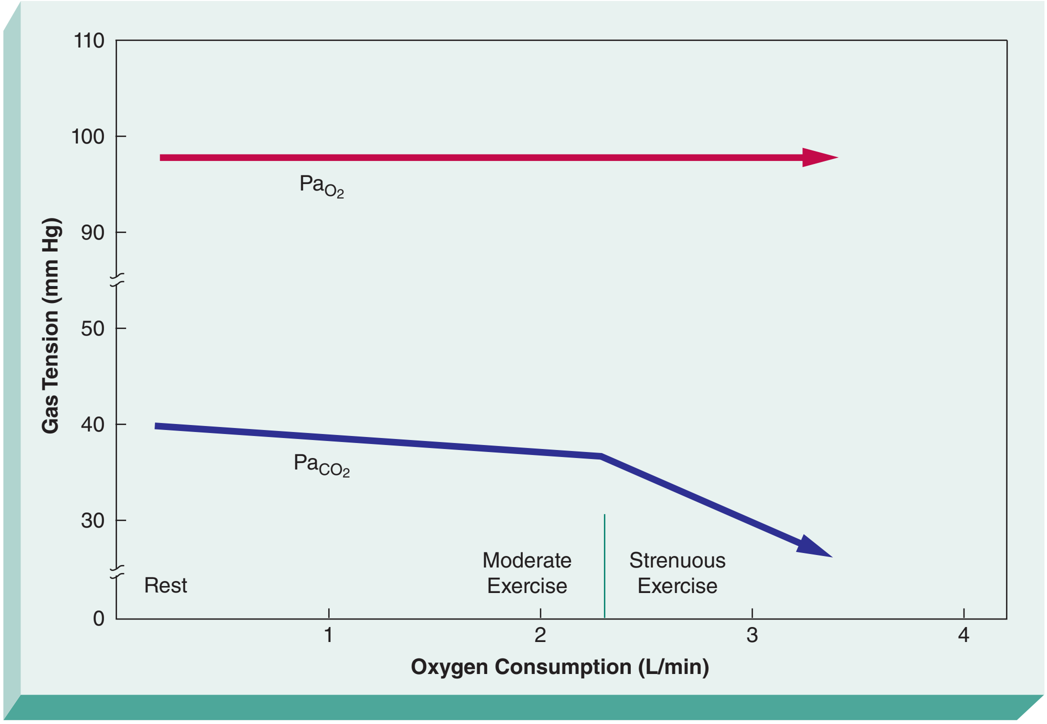


FIGURE 18-5 Oxygen diffusion capacity increases linearly in response to increased oxygen consumption as the intensity of exercise increases.

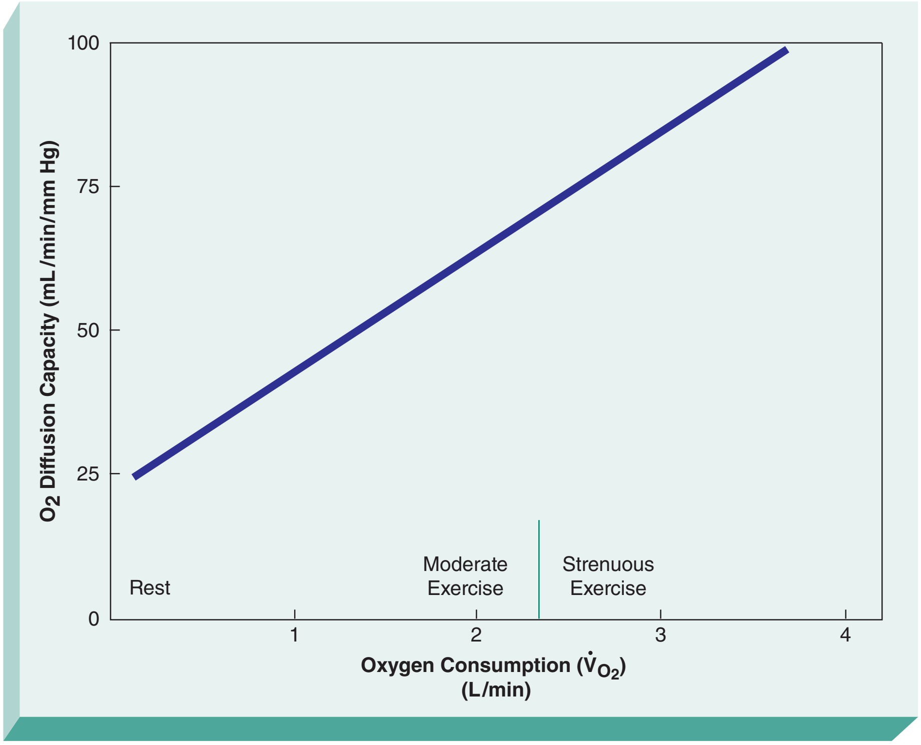
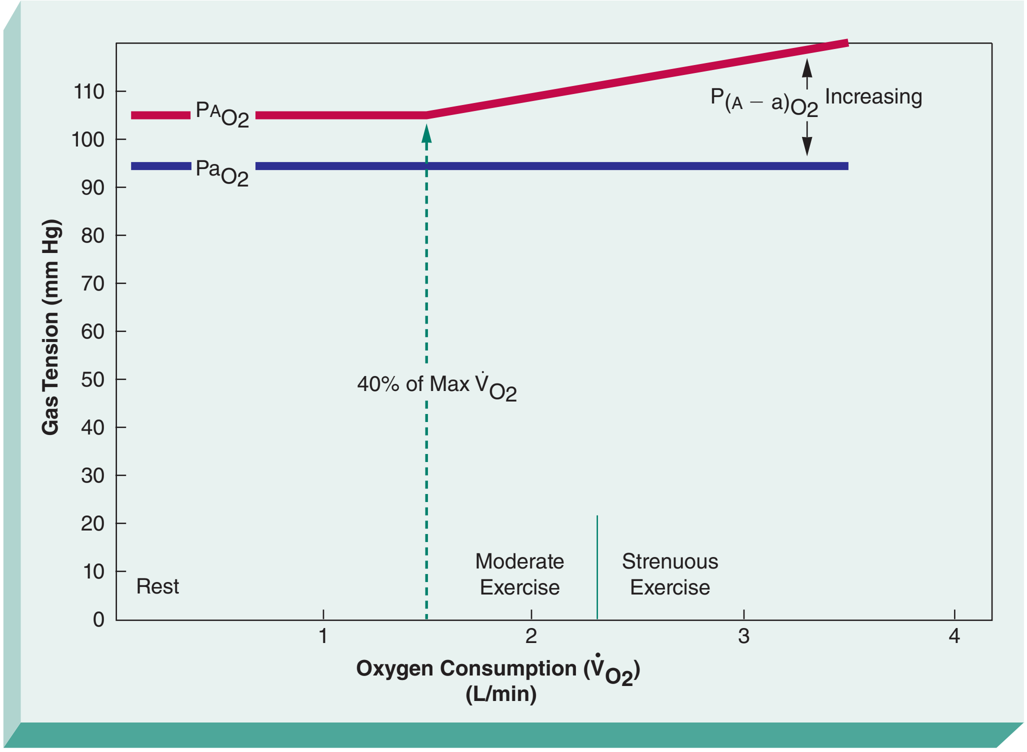


FIGURE 18-6 The alveolar-arterial oxygen tension difference $P_{(A-a)O_2}$ begins to increase when approximately 40 percent of the maximal $\dot{V}_{O_2}$ is exceeded.



constant until 40 percent of the maximal $\dot{V}_{O_2}$ is reached; beyond this point, the $P_{(A-a)O_2}$ begins to increase (Figure 18–6). An average $P_{(A-a)O_2}$ of 33 mm Hg has been reported for endurance runners exercising at their maximal $\dot{V}_{O_2}$.

Circulatory Functions

Heavy exercise is one of the most stressful conditions the circulatory system encounters. Blood flow to the working muscles may increase as much as 25-fold, and the total cardiac output may increase as much as 8-fold.

The ability of an individual to increase cardiac output to the muscles is the major determinant of how long and to what intensity the exercise can be sustained. In fact, the speed of a marathon runner or swimmer is almost directly proportional to the athlete's ability to increase his or her cardiac output. Thus, the circulatory system is as important as the muscles themselves in setting the limits for exercise.

During exercise, the following essential physiologic responses must occur in order for the circulatory system to supply the working muscles with an adequate amount of blood: (1) sympathetic discharge, (2) increase in cardiac output, (3) increase in arterial blood pressure, (4) increase in pulmonary vascular pressures, and (5) dilation of muscle capillaries.

Sympathetic Discharge

At the onset of exercise, the brain transmits signals to the vasomotor center in the medulla oblongata to trigger a sympathetic discharge. This sympathetic discharge has two circulatory effects: (1) the heart is stimulated to increase its rate and strength of contraction, and (2) the blood vessels of the peripheral vascular system constrict, except for the blood vessels of the working muscles, which strongly dilate in response to local vasodilators in the muscles themselves. The net result is an increased blood supply to the working muscles while the blood flow to nonworking muscles is reduced. Note that vasoconstriction in the heart and brain does not occur during exercise because both the heart and the brain are as important to exercise as the working muscles themselves.

Increase in Cardiac Output

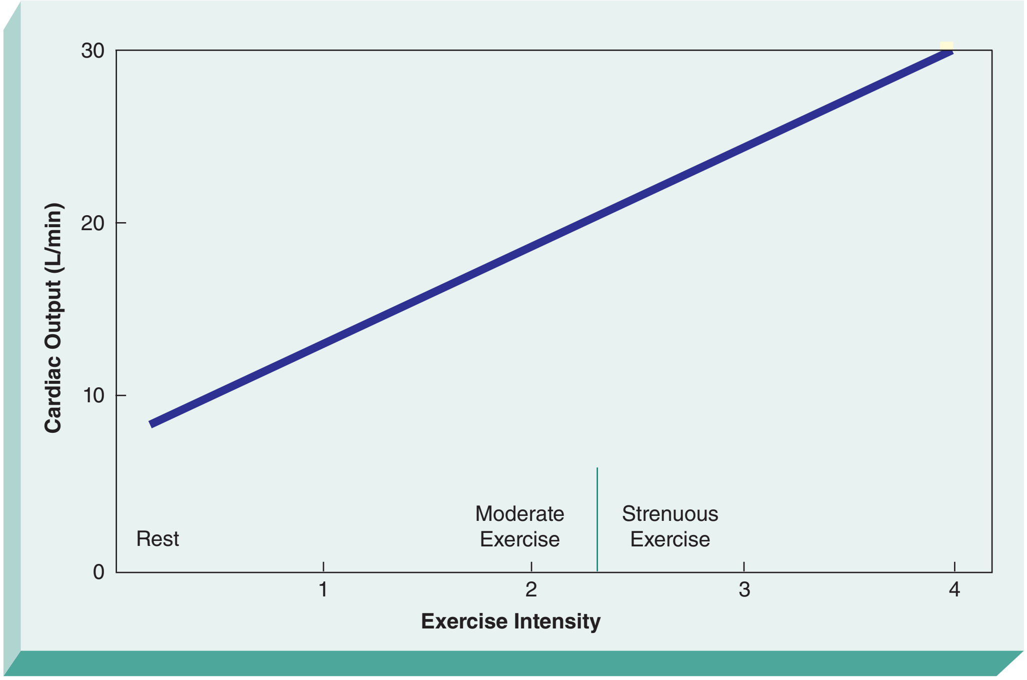
The increased oxygen demands during exercise are met almost entirely by an increased cardiac output. Figure 18–7 shows the linear relationship between the cardiac output and the intensity of exercise. The increased cardiac output during exercise results from (1) increased stroke volume, (2) increased heart rate, or (3) a combination of both.

Increased Stroke Volume

The increased stroke volume during exercise is primarily due to vasodilation in the working muscles; that is, the vasodilation in the working muscles increases the venous return to the heart. The heart, in turn, pumps more oxygenated blood back to the working muscles. Thus, the degree of vasodilation in the working muscles directly influences the stroke volume; therefore, the greater the vasodilation in the working muscles, the greater the stroke volume and cardiac output. Another factor that facilitates an increased venous return during exercise is the sympathetic discharge. This causes a constriction of all venous blood reservoirs and forces more blood out of the veins and toward the heart.

As discussed in Chapter 5, the ability of the heart to accommodate the increased venous return and, subsequently, increase the cardiac output is due to the Frank-Starling curve (refer to Figure 5–28). When more venous blood returns to the heart, the heart chambers increase in size to accommodate the increased volume. As the heart chambers increase in size, the force of the heart muscle contractions increase, which in turn increases the stroke volume.

FIGURE 18-7 A linear relationship exists between cardiac output and the intensity of exercise.



In addition to the Frank-Starling curve, the heart is also strongly stimulated by the sympathetic discharge. Increased sympathetic stimulation causes (1) increased heart rate (as high as 200 bpm) and (2) increased strength of contraction. The combined effect of these two mechanisms greatly increases the heart's ability to pump blood beyond what could be accomplished by the Frank-Starling curve alone.

Increased Heart Rate

An individual's maximum heart rate is estimated by the following formula:

Maximum heart rate = 220 − Age (in years)

Thus, the maximum heart rate for a 45-year-old person is about 175 (220 − 45 = 175).

Although the heart rate increases linearly with oxygen consumption, the magnitude of the change is influenced by the size of the stroke volume; that is, when the stroke volume decreases, the heart rate increases, and when the stroke volume increases, the heart rate decreases. The stroke volume, in turn, is influenced by (1) the individual's physical condition, (2) the specific muscles that are working, and (3) the distribution of blood flow. The body's ability to increase the heart rate and stroke volume during exercise progressively declines with age.

Increase in Arterial Blood Pressure

There is an increase in arterial blood pressure during exercise because of the (1) sympathetic discharge, (2) increased cardiac output, and (3) vasoconstriction of the blood vessels in the nonworking muscle areas. Depending on the physical condition of the individual, as well as the intensity and duration of the exercise, the systolic arterial blood pressure may increase as little as 20 mm Hg or as much as 80 mm Hg.

Increase in Pulmonary Vascular Pressures

As oxygen consumption and cardiac output increase during exercise, the systolic, diastolic, and mean pulmonary arterial and wedge pressures also increase linearly (Figure 18–8). As discussed earlier, this mechanism enhances oxygen uptake by (1) distending the pulmonary capillaries and (2) opening closed pulmonary capillaries.

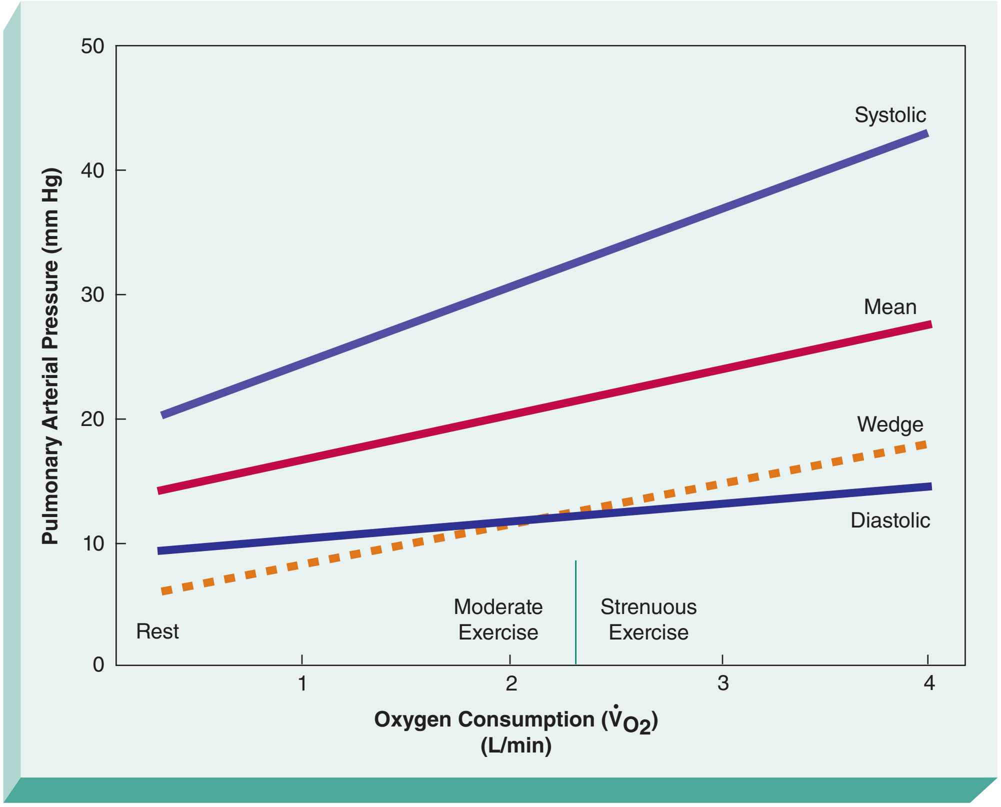
Dilation of Muscle Capillaries

At rest, approximately 20 to 25 percent of the muscle capillaries are dilated. During heavy exercise, all the capillaries dilate to facilitate the distribution of blood. This reduces the distance that oxygen and other nutrients must travel from the capillaries to the muscle fiber. At the same time, the blood vessels of the viscera and nonworking muscles constrict.

The dilation of the blood vessels in the working muscles is caused primarily by local vasodilators acting directly on the arterioles. The most important local vasodilator effect is the reduction of oxygen in the working muscles. It is suggested that a diminished oxygen concentration in the muscles causes vasodilation because either (1) the vessels are unable to maintain contraction at low oxygen levels or (2) low oxygen levels cause the release of vasodilator substances. The most likely vasodilator substance is *adenosine*. Other vasodilator substances include potassium ions, acetylcholine, adenosine triphosphate, lactic acids, and carbon dioxide. The precise role of each of these substances in increasing blood flow to working muscles is not known.

Finally, because the vasodilation of the major working muscle groups is greater than the vasoconstriction of the nonworking muscle groups, the overall peripheral vascular resistance decreases. This is why elite athletes can substantially increase their cardiac output with only a slight increase in their mean systemic arterial blood pressure. Untrained individuals have a high peripheral vascular resistance and, therefore, high arterial blood pressure in response to modest increases in cardiac output during exercise.

FIGURE 18-8 The systolic, diastolic, and mean pulmonary arterial and wedge pressures increase linearly as oxygen consumption and cardiac output increase.



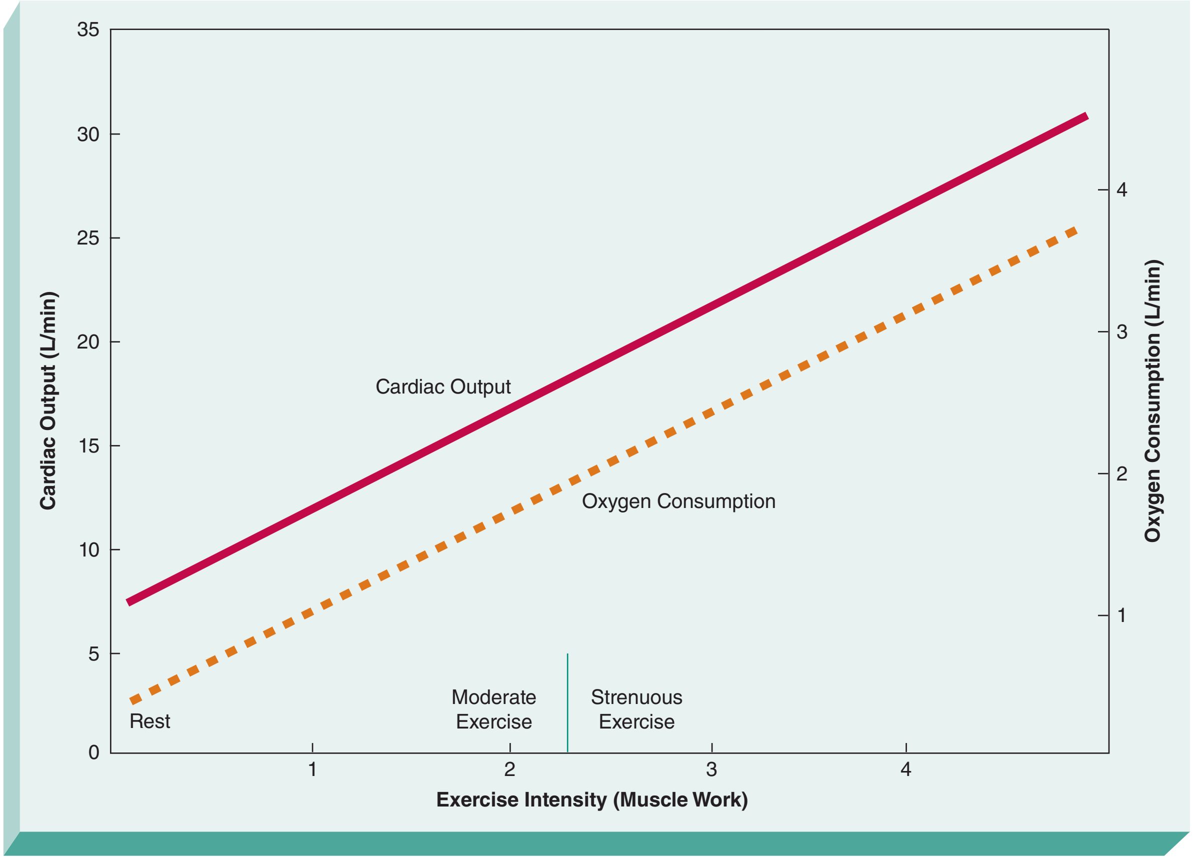
Interrelationships among Muscle Work, Oxygen Consumption, and Cardiac Output

Figure 18–9 shows that muscle work, oxygen consumption, and cardiac output are all related to each other. Increased muscle work increases oxygen consumption, and the increased oxygen consumption, in turn, dilates the intramuscular blood vessels. As the intramuscular blood vessels dilate, venous return increases, causing the cardiac output to rise. Marathon runners can have a cardiac output as great as 40 L/min. The maximum cardiac output of a young, untrained individual is less than 25 L/min.

Influence of Training on the Heart and Cardiac Output

The increased cardiac output seen in marathon runners results mainly from the fact that the heart chambers and heart mass increase as much as 40 percent. Cardiac enlargement and increased pumping ability occur only in the endurance type of athletic training and not in the sprint type of activity. The "athlete's heart" is an effective and physiologically sound heart. It should not be considered a pathologic heart. At rest, the cardiac output of the elite athlete is almost the same as that of the average untrained individual. The former, however, has a greater stroke volume and a reduced heart rate.

FIGURE 18-9 Relationship among muscle work, oxygen consumption, and cardiac output.

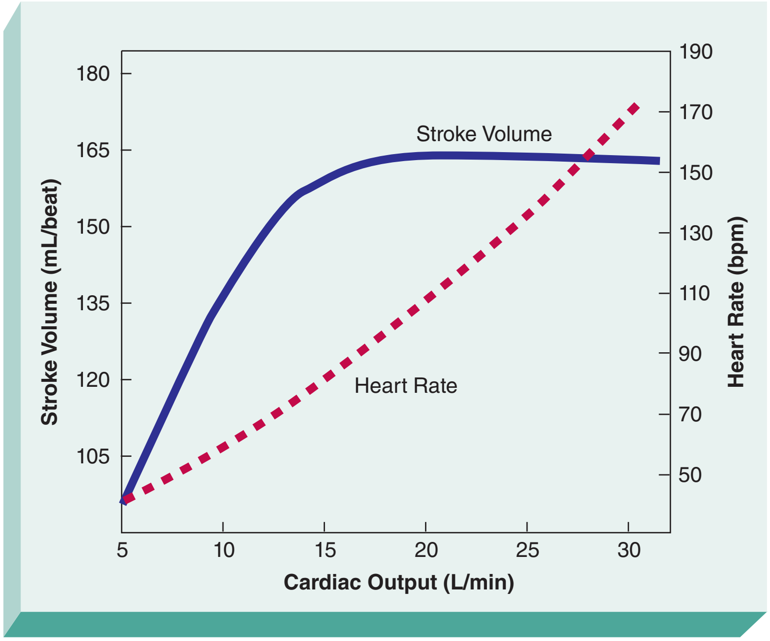


Stroke Volume versus Heart Rate in Increasing Cardiac Output

Figure 18–10 shows the approximate changes that occur in stroke volume and heart rate as the cardiac output increases from about 5 to 30 L/min in a marathon runner. The stroke volume increases from about 100 mL to about 150 mL, an increase of about 50 percent. The heart rate increases from 50 to 180 beats/min, an increase of 260 percent. Thus, during very strenuous exercise, the increase in heart rate accounts for a much greater proportion of the increased cardiac output than the increase in stroke volume. In fact, the stroke volume reaches its maximum when the maximum cardiac output is at only approximately 50 percent. Thus, any further increase in cardiac output beyond the midway point is due solely to the increased heart rate.

At maximum exercise, cardiac output reaches about 90 percent of the maximum that can be achieved. Because maximum exercise taxes the respiratory system only about 65 percent of maximum, it can be seen that normally the cardiovascular system is a greater limiting factor on maximal exercise than the respiratory system. Thus, the maximum performance that a marathon runner can achieve is directly related to the condition of the cardiovascular system. Any type of heart disease that reduces the heart's ability to pump blood will also decrease an individual's muscle power. This explains, in part, why a patient with congestive heart failure may have difficulty in generating enough muscle power to climb out of bed or to walk short distances.

FIGURE 18-10 Approximate changes in stroke volume and heart rate that occur when the cardiac output increases from about 5 to 30 L/min in a marathon runner.



Clinical Connection 18-1

General Benefits of Exercise

In addition to the well-documented cardiopulmonary benefits associated with exercise, even a moderate amount of exercise is strongly connected to the following benefits:

- Reduced stress
- Reduced weight
- Reduced symptoms of depression and anxiety
- Reduced risk of developing diabetes
- Reduced cholesterol levels
- Increased mood and energy
- Improved sleep
- Increased bone density
- Building and maintenance of healthy muscles
- Improved quality of life

Body Temperature/Cutaneous Blood Flow Relationship

During exercise, the body generates a tremendous amount of heat, and heat production may increase as much as 20-fold. Although some of the heat is stored in the body during exercise, most of the heat is dissipated through the skin. This requires a substantial increase in blood flow to the body surface. Nevertheless, even during normal temperature and humidity conditions, the body temperature may rise from its normal 98.6°F to 102°F to 103°F (37°C to 40°C) during endurance athletics.

When exercise is performed during very hot and humid conditions, or without adequately ventilated clothing, heat loss may be impaired, and an unusually large amount of blood may be distributed to the skin. During these conditions, the body temperature can easily rise from 106°F to 108°F (41°C to 42°C). As much as 5 to 10 lb of body fluid can be lost in 1 hour. When this happens, a number of signs and symptoms may appear, which collectively are referred to as **heat stroke**. These signs and symptoms include the following:

- Profuse sweating, followed by no sweating
- Extreme weakness
- Muscle cramping
- Exhaustion
- Nausea
- Headache
- Dizziness
- Confusion
- Staggering gait
- Altered level of consciousness
- Unconsciousness
- Circulatory collapse

Heat stroke can be fatal if not treated immediately. Even when the individual stops exercising, the temperature does not readily return to normal because (1) the temperature-regulating mechanism often fails at a very high temperature and (2) the intracellular metabolism is much faster at higher temperatures, which in turn generates still more heat.

The primary treatment of heat stroke is to reduce the victim's body temperature as fast as possible. This is done by (1) spraying cool water on the victim's body, (2) continually sponging the victim with cool water, (3) blowing air over the body with a strong fan, or (4) a combination of all three measures.

Pulmonary Rehabilitation

Pulmonary rehabilitation is now a well-accepted, multidisciplinary health care service for patients with chronic obstructive pulmonary disease (COPD). It provides patients with a process of developing and maintaining a desirable level of physical, social, and psychological well-being. The typical pulmonary rehabilitation team consists of a physician, nurse, respiratory therapist, physical therapist, psychologist or social worker, and dietitian. The primary goal of the program is to achieve and maintain the patient's maximum level of independence and functioning in the community. Table 18–1 provides an overview of the major components of a pulmonary rehabilitation program.

Pulmonary rehabilitation programs are commonly divided into the following three phases.

Phase I

Phase I typically begins while the patient is in the hospital. This phase is the pretesting portion of the program. The patient performs a variety of tests such as pulmonary function studies, stress tests, and 6- to 12-minute walking tests. During this phase, the patient is also evaluated for any nutritional, psychological, lifestyle, and vocational needs.

TABLE 18-1 Components of Pulmonary Rehabilitation

General Factors • Patient and family education • Nutrition instruction and weight control • Avoidance of smoking and inhaled irritants • Avoidance of infections (e.g., immunization) • Proper living environment • Proper hydration
Medications • Bronchodilators • Expectorants • Antimicrobials • Corticosteroids • Cromolyn sodium/nedocromil sodium • Leukotriene antagonists/inhibitors • Diuretics • Psychopharmacologic agents
Respiratory Therapy Modalities • Aerosol therapy • Oxygen therapy • Home ventilators
Physical Therapy Modalities • Relaxation training • Breathing retraining • Chest percussion and postural drainage • Deliberate coughing and expectoration • Exercise conditioning
Occupational Therapy • Evaluate activities of daily living • Outline energy-conserving maneuvers • Psychosocial rehabilitation
Vocational Rehabilitation

Based on information from Hodgkin JE, Celli BR, Connors GL (2009). *Pulmonary Rehabilitation Guidelines to Success* (4th ed.). Mosby/Elsevier.

Phase II

Phase II is the 10- to 12-week outpatient therapy part of the program. This phase includes patient and family education, group and individual counseling, and group discussion sessions. Educational topics include basic cardiopulmonary anatomy and physiology, breathing techniques, pulmonary hygiene, nutritional guidelines, medications, respiratory therapy equipment, and the importance of exercise. During this phase, the patient begins active range-of-motion exercises. Such exercises include work on the treadmill, air-dyne bike, arm ergometer, and rowing machine plus chest pulleys and steps. The primary objective during this phase is the conditioning of the cardiovascular system (aerobic) and skeletal muscles. During the last portion of this phase, long-term graded exercises are emphasized, such as walking, jogging, stationary bicycling, and/or swimming.

Phase III

Phase III is designed to help the patient become more independent and responsible for his or her own exercise program. Phase III consists of follow-up care and long-term maintenance. Components of this phase include efforts to modify risk factors (e.g., control of blood lipids, hypertension, obesity, smoking cessation) and the establishment of a routine program of physical activity. This phase should continue indefinitely.

TABLE 18-2 **Benefits of Pulmonary Rehabilitation in COPD**

- Exercise capacity is improved.
- Patient's perceived intensity of breathlessness is reduced.
- Health-related quality of life is improved.
- Number of hospitalizations and days in the hospital are reduced.
- Anxiety and depression associated with COPD are reduced.
- Strength and endurance training of the upper limbs improve arm function.
- Benefits extend well beyond the immediate period of training.
- Survival rate is improved.
- Respiratory muscle training is beneficial—especially when combined with general exercise training.
- Psychological intervention is helpful.
- Become educated about COPD and medications.

The patient commonly undergoes yearly evaluation, which includes graded exercise testing. Some patients may require more frequent evaluations.

Table 18–2 provides an overview of the benefits associated with pulmonary rehabilitation for the COPD patient.

Chapter Summary

A basic knowledge of the effects of exercise on the cardiopulmonary systems is helpful to the respiratory therapist. Important topics regarding ventilation during exercise include the control of ventilation, alveolar ventilation, oxygen consumption, arterial blood gas values, increased oxygen diffusion capacity, and alveolar-arterial difference. In addition, exercise has a significant effect on circulation. Topics in this area include sympathetic discharge, cardiac output, arterial blood pressure, pulmonary vascular pressure, and the dilation of muscle capillaries. In addition, a basic understanding of the following should be mastered: the interrelationship among muscle work, oxygen consumption, and cardiac output; the influence of training on the heart and on cardiac output; and the relationship between body temperature and cutaneous blood flow. Finally, the respiratory therapist should know the primary components of the three phases of a pulmonary rehabilitation program. A clinical connection associated with these topics includes the general benefits of exercise.

Review Questions

1. During strenuous exercise, an adult's alveolar ventilation can increase as much as

A. 10-fold
B. 20-fold
C. 30-fold
D. 40-fold

2. The maximum alveolar ventilation generated during heavy exercise under normal conditions is about what percent of the maximum voluntary ventilation?

A. 20–35 percent
B. 30–45 percent
C. 40–55 percent
D. 50–65 percent

3. During heavy exercise, the total cardiac output may increase as much as

A. 2-fold
B. 4-fold
C. 6-fold
D. 8-fold

4. At the onset of exercise, sympathetic discharge causes the

1. Heart rate to decrease
2. Peripheral vascular system to constrict

3. Heart to increase its strength of contraction
4. Blood vessels of the working muscles to dilate
   - A. 3 only
   - B. 2 and 4 only
   - C. 1 and 2 only
   - D. 2, 3, and 4 only

5. During exercise, the stroke volume reaches its peak when the cardiac output is at about what percent of its maximum?

A. 30 percent
B. 40 percent
C. 50 percent
D. 60 percent

6. During exercise, heat production may increase as much as

A. 10-fold
B. 20-fold
C. 30-fold
D. 40-fold

7. During exercise, the oxygen consumption ($\dot{V}_{O_2}$) of the skeletal muscles may account for more than

A. 65 percent of the total $\dot{V}_{O_2}$
B. 75 percent of the total $\dot{V}_{O_2}$
C. 85 percent of the total $\dot{V}_{O_2}$
D. 95 percent of the total $\dot{V}_{O_2}$

8. During very heavy exercise, the

1. pH increases
2. Pa_{CO_2} decreases
3. Pa_{O_2} remains constant
4. pH decreases
5. Pa_{CO_2} increases
   - A. 1 and 2 only
   - B. 4 and 5 only
   - C. 2 and 4 only
   - D. 2, 3, and 4 only

9. During maximum exercise, the oxygen diffusion capacity may increase as much as

A. 3-fold
B. 6-fold
C. 9-fold
D. 12-fold

10. During exercise, the $P_{(A-a)O_2}$ begins to increase when the oxygen consumption reaches about what percent of its maximum?

A. 10 percent
B. 20 percent
C. 30 percent
D. 40 percent

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CHAPTER 19

High Altitude and Its Effects on the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the effects of high altitude on the cardiopulmonary system.
2. Describe other physiologic changes caused by high altitude.

Cardiopulmonary Changes Seen at High Altitude

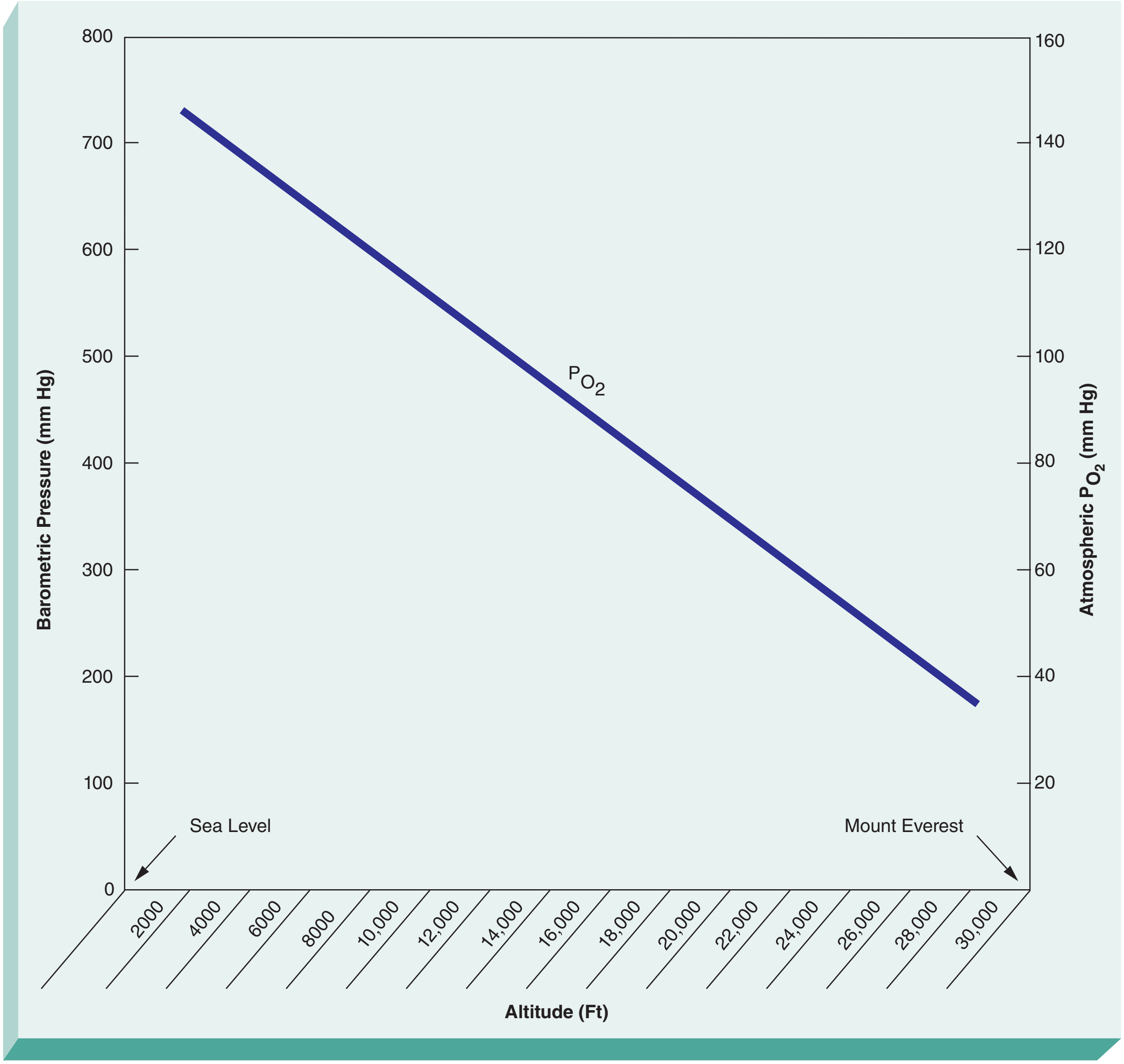
The effects of high altitude on the cardiopulmonary system are of interest because better understanding of long-term oxygen deprivation can be applied to the treatment of chronic hypoxia caused by lung disease. Nearly 30 million people live at altitudes greater than 8000 feet—mostly in the Rocky Mountains of North America, the Andes Mountains of South America, the Himalaya Mountains of south central Asia, and the Ethiopian Highlands of East Africa. In addition, many lowlanders travel to high altitudes for work and recreation. Unfortunately, these short-term, high-altitude exposures also pose the hazards of acute altitude illnesses. The purpose of this chapter is to review both the normal responses and adaptive processes that occur in response to high altitude.

Under normal conditions, the barometric pressure—and P_{O_2}—progressively decreases with altitude (Figure 19–1). At an altitude of 18,000 to 19,000 feet, the barometric pressure is about half the sea-level value of 760 mm Hg (380 mm Hg). The barometric pressure on the summit of Mount Everest (altitude: 29,028 feet) is about 250 mm Hg (the atmospheric P_{O_2} is about 43 mm Hg). At an altitude of about 65,000 feet, the barometric pressure falls below the pressure of water vapor, and tissue fluids begin to "boil" or "vaporize." Table 19–1 provides an overview of the altitude (in feet and meters), barometric pressure, and inspired P_{O_2} relationship.

When an individual who normally lives near sea level spends a period of time at high altitudes, a number of compensatory responses develop—a process known as acclimatization. For example, it is an interesting fact that after a period of acclimatization, an individual may reach the summit of Mount Everest without supplemental oxygen. However, when an individual is suddenly exposed to the oxygen tension found at the summit of Mount Everest, a loss of consciousness occurs within minutes.

The following are some of the primary cardiopulmonary changes seen at high altitude.

FIGURE 19-1 The barometric pressure and the atmospheric P_{O_2} decrease linearly as altitude increases.



Ventilation

One of the most prominent features of acclimatization is increased alveolar ventilation. As already mentioned, when an individual ascends above the Earth's surface, the barometric pressure progressively decreases, and the atmospheric P_{O_2} declines. As the atmospheric P_{O_2} decreases, the individual's arterial oxygen pressure (Pa_{O_2}) also decreases. Eventually, the Pa_{O_2} will fall low enough (to about 60 mm Hg) to stimulate the carotid and aortic bodies, known collectively as the **peripheral chemoreceptors** (refer to Figure 9–4).

When the peripheral chemoreceptors are stimulated, they transmit signals to the medulla to increase ventilation (refer to Figure 9–5). This response is called the **hypoxic ventilator response (HVR)**. The HVR works to minimize the drop in alveolar P_{O_2}. Because the peripheral chemoreceptors do not acclimate to a decreased oxygen concentration, increased alveolar ventilation will continue for the entire time the individual remains at the high altitude.[1]

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[1] See Clinical Application Case 1, Chapter 9.

TABLE 19-1 The Altitude, Barometric Pressure, and Inspired P_{O_2} Relationship

Altitude (meters)	Altitude (feet)	Barometric Pressure (mm Hg)	Inspired P_{O_2} (mm Hg)
0	0	760	159
1,000	3,280	674	141
2,000	6,560	596	125
3,000	9,840	526	110
4,000	13,120	463	97
5,000	16,400	405	85
6,000	19,680	354	79
8,000	26,240	268	56
8,848	29,028	253	43

Based on information from Luks AM, Schoene RB. High Altitude. In *Murray & Nadel's Textbook of Respiratory Medicine* (5th ed.). Editors: Mason RJ, Broaddus CV, Saunders/Elsevier, 2010, pp. 1651–1673.

Pulmonary Function and Mechanics

As an individual ascends, the following changes occur in lung function as a result of acute hypoxic exposure: The vital capacity decreases within the first 24 hours. It is believed the causes of the reduced vital capacity include increased interstitial lung fluid—which in turn results in airway narrowing, air trapping, and delayed emptying of alveolar gas—pulmonary vascular engorgement, and decreased respiratory muscle strength. It is interesting to note that the peak expiratory flow rates are actually increased. It is believed that this lower airway resistance is due, in part, to the decreased air density, which works to offset any airway narrowing.

Unlike individuals exposed to acute hypoxic environments, long-term high-altitude residents have an increased vital capacity. Research shows a direct relationship to the vital capacity size and the length of time one resides at high altitudes—that is, the more time spent at high altitudes, the larger the vital capacity. People born and raised at high altitudes develop larger vital capacities than those who reside in high altitudes later in life.

Polycythemia

When an individual is subjected to a low concentration of oxygen for a prolonged period of time, the hormone *erythropoietin* from the kidneys stimulates the bone marrow to increase red blood cell (RBC) production. The increased hemoglobin available in polycythemia is an adaptive mechanism that increases the oxygen-carrying capacity of the blood. In fact, people who live at high altitudes often have a normal, or even above-normal, oxygen-carrying capacity, despite a chronically low Pa_{O_2} and oxygen saturation.

In lowlanders who ascend to high altitudes, the RBCs increase for about 6 weeks before the production rate levels off. As the level of RBCs increases, the plasma volume decreases. Thus, there is no significant change in the total circulating blood volume. After 6 weeks, an average hemoglobin concentration of 20.5 g/dL has been observed in mountain climbers who climbed to altitudes greater than 18,000 feet.

Acid–Base Status

Because of the increased ventilation generated by the peripheral chemoreceptors at high altitudes, the Pa_{CO_2} decreases, causing a secondary respiratory alkalosis. Over a 24- to 48-hour period, the renal system tries to offset the respiratory alkalosis by eliminating some of the excess bicarbonate. In spite of this mechanism, however, a mild respiratory alkalosis usually persists. In fact, even natives who have been at high altitudes for generations commonly have a mild respiratory alkalosis.

It is assumed that respiratory alkalosis may be advantageous for the transfer of oxygen across the alveolar-capillary membrane because alkalosis increases the affinity of hemoglobin for oxygen. In other words, the alkalosis enhances the loading of oxygen to the hemoglobin as desaturated blood passes through the alveolar-capillary system. It is also argued, however, that the increased affinity interferes with the unloading of oxygen at the cells.

There is both experimental and theoretical evidence that the increased oxygen affinity at high altitude is beneficial. This is further supported by the fact that a mild respiratory alkalosis usually persists in mountain climbers, high-altitude natives, and even in animals who live in low-oxygen environments. The alkalosis persists even after the kidneys have had more than enough time to fully eliminate the excess bicarbonate.

Oxygen Diffusion Capacity

In response to short-term exposure to high altitude, there are a number of factors that limit oxygen diffusion. The decreased barometric pressure lowers the alveolar P_{O_2}, which in turn reduces the pressure gradient for diffusion. At altitudes greater than 2500 meters, even the estimated at-rest pulmonary capillary transit time of 0.75 second may not be adequate for end-capillary equilibration of oxygen to occur. This diffusion limitation is exacerbated during exercise because of the shortened transit time of blood moving through the alveolar-capillary system.

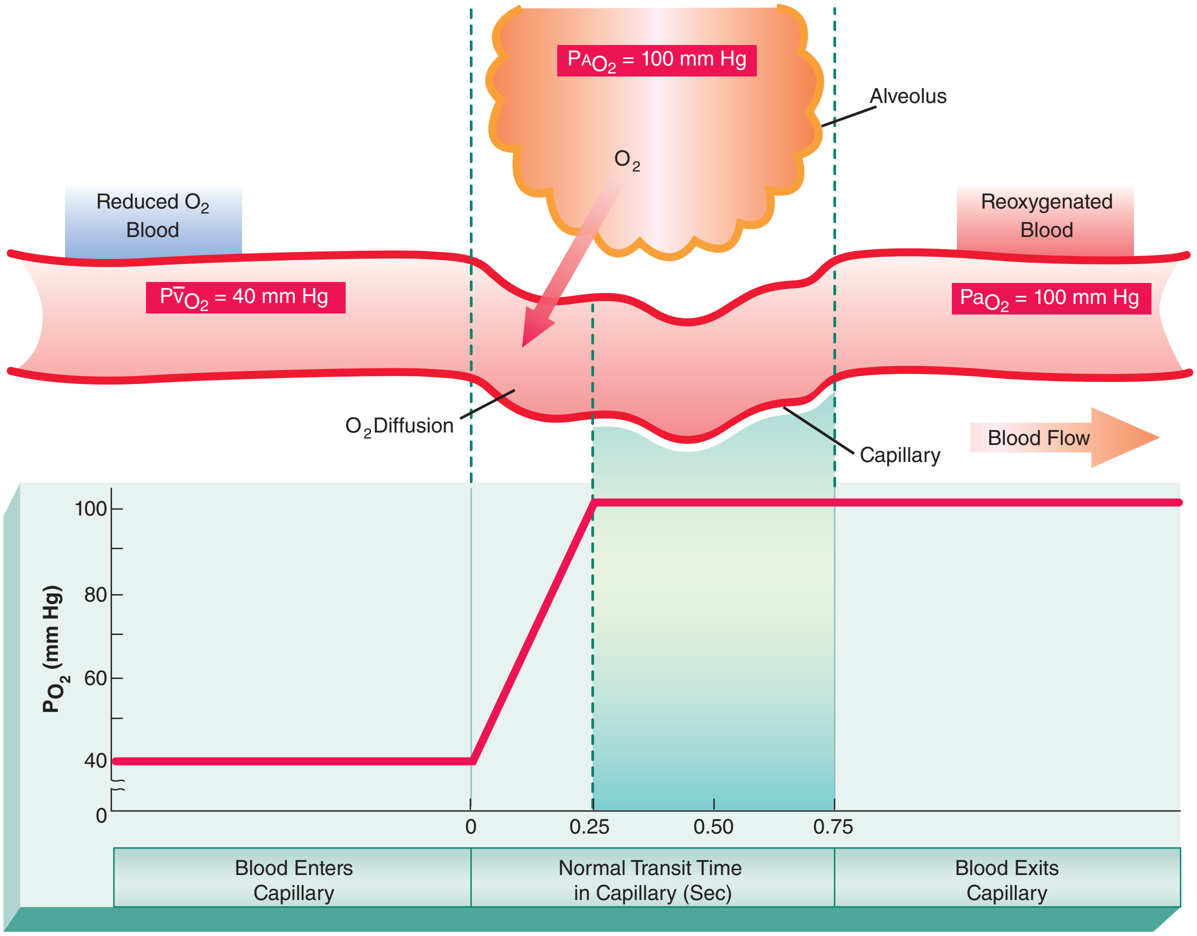
With long-term residence at high altitude, there is a remarkable change in the oxygen diffusion capacity, although the mechanism remains unclear. Individuals residing at high-altitude have a lower alveolar-arterial P_{O_2} difference, an increased diffusing capacity, and higher arterial P_{O_2} at rest and exercise. High-altitude natives have been shown to have an oxygen diffusion capacity that is about 20 to 25 percent greater than predicted, both during rest and exercise. The increased oxygen diffusion may be explained, in part, by the polycythemia that often develops at high altitudes. Increased numbers of red blood cells increase the diffusion capacity of oxygen (refer to Table 4–3).

The increased oxygen diffusion may also be explained by the larger lung volumes or capacities seen in high-altitude natives. It is suggested that the larger lungs provide an increased alveolar surface area and a larger capillary blood volume. This is further supported by studies that demonstrate that when animals are exposed to low-oxygen partial pressures during their active growth period, they develop larger lungs and greater diffusion capacity. On the other hand, animals exposed to high concentrations of oxygen during their active growth period develop smaller lungs than expected.

Alveolar-Arterial P_{O_2} Difference

During acute high-altitude exposures, oxygen diffusion across the alveolar-capillary membrane is limited, which results in an increased **alveolar-arterial oxygen tension difference** ($P_{(A-a)O_2}$). Figure 19–2 shows that under normal circumstances, there is ample time for oxygen to equilibrate between the alveoli and the end-capillary blood. In contrast, Figure 19–3 shows the estimated time necessary for oxygen to equilibrate for a climber at rest on the summit of Mount Everest. Note that the pulmonary blood enters the alveolar-capillary system with a P_{O_2} of about 21 mm Hg and slowly rises to about 28 mm Hg. Thus, as the blood leaves the alveolar-capillary system, there is a large $P_{(A-a)O_2}$ characteristic of oxygen diffusion limitations. In other words, only 80 percent of the P_{O_2} (P_{O_2} of 28 mm Hg divided by a $P_{A_{O_2}}$ of 35 = 0.80) actually moved across the alveolar-capillary membrane. Twenty percent of the $P_{A_{O_2}}$ did not move across the alveolar-capillary membrane into the capillary blood. At high altitude, the $P_{(A-a)O_2}$ is further increased (1) during exercise—because of the increased cardiac output—and (2) in individuals with alveolar thickening caused by interstitial lung disease.

FIGURE 19-2 Under normal resting conditions, blood moves through the alveolar-capillary membrane in about 0.75 second. The oxygen pressure P_{O_2} reaches equilibrium in about 0.25 second—one-third of the time available.


$P_{A_{O_2}}$ = 100 mm Hg
Alveolus
O_2
Reduced O_2 Blood
Reoxygenated Blood
$P\bar{v}_{O_2}$ = 40 mm Hg
Pa_{O_2} = 100 mm Hg
O_2 Diffusion
Capillary
Blood Flow
P_{O_2} (mm Hg)
100
80
60
40
0
0
0.25
0.50
0.75
Blood Enters Capillary
Normal Transit Time in Capillary (Sec)
Blood Exits Capillary

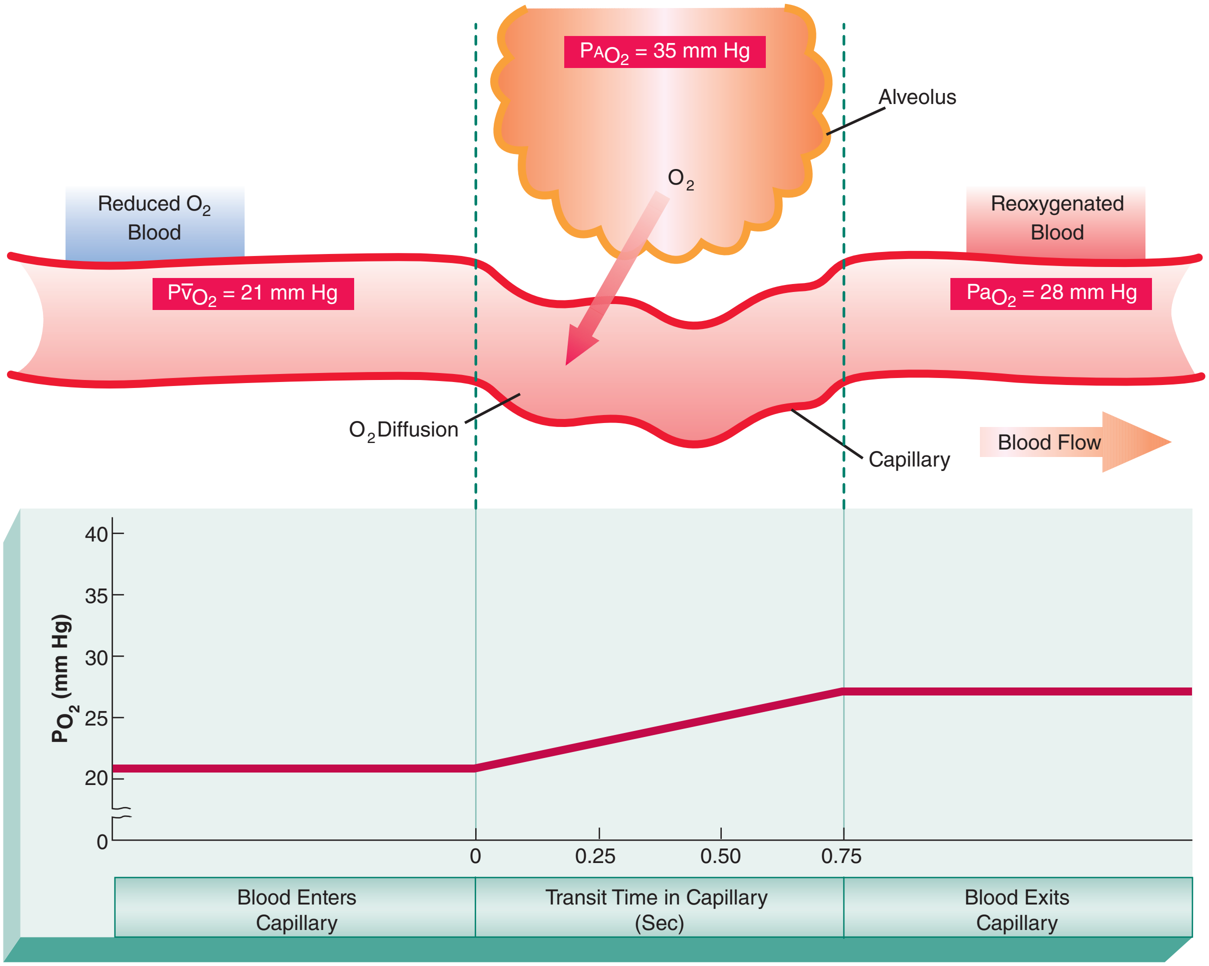
Ventilation–Perfusion Relationships

At high altitude, the increased ventilation is matched by increased cardiac output and pulmonary perfusion. In addition, the acute alveolar hypoxia activates hypoxic pulmonary vasoconstriction (HPV), which in turn increases pulmonary vascular resistance. These mechanisms cause the redistribution of pulmonary blood flow to areas of the lung that are not as well perused at sea level—thus, improving the overall ventilation–perfusion ratio and optimizing gas exchange.

Cardiac Output

During acute exposure to a hypoxic environment, the cardiac output during both rest and exercise increases, which in turn increases the oxygen delivery to the peripheral cells. In individuals who have acclimatized to high altitude, however, and in high altitude natives, increased cardiac output is not seen. Cardiac output and oxygen uptake are the same as at sea level. The precise reason for the return of the cardiac output and oxygen uptake to sea level values is unknown. It has been suggested that the polycythemia that develops in well-acclimatized subjects may play a role.

FIGURE 19-3 Estimated time necessary for oxygen diffusion for a climber at rest on the summit of Mount Everest. As the blood leaves the alveolar-capillary system, there is a large alveolar-arterial oxygen tension difference $P_{(A-a)O_2}$.


$P_{A_{O_2}}$ = 35 mm Hg
Alveolus
O_2
Reduced O_2 Blood
Reoxygenated Blood
$P\bar{v}_{O_2}$ = 21 mm Hg
Pa_{O_2} = 28 mm Hg
O_2 Diffusion
Capillary
Blood Flow
PO_2 (mm Hg)
40
35
30
25
20
0
0
0.25
0.50
0.75
Blood Enters Capillary
Transit Time in Capillary (Sec)
Blood Exits Capillary

Pulmonary Vascular System

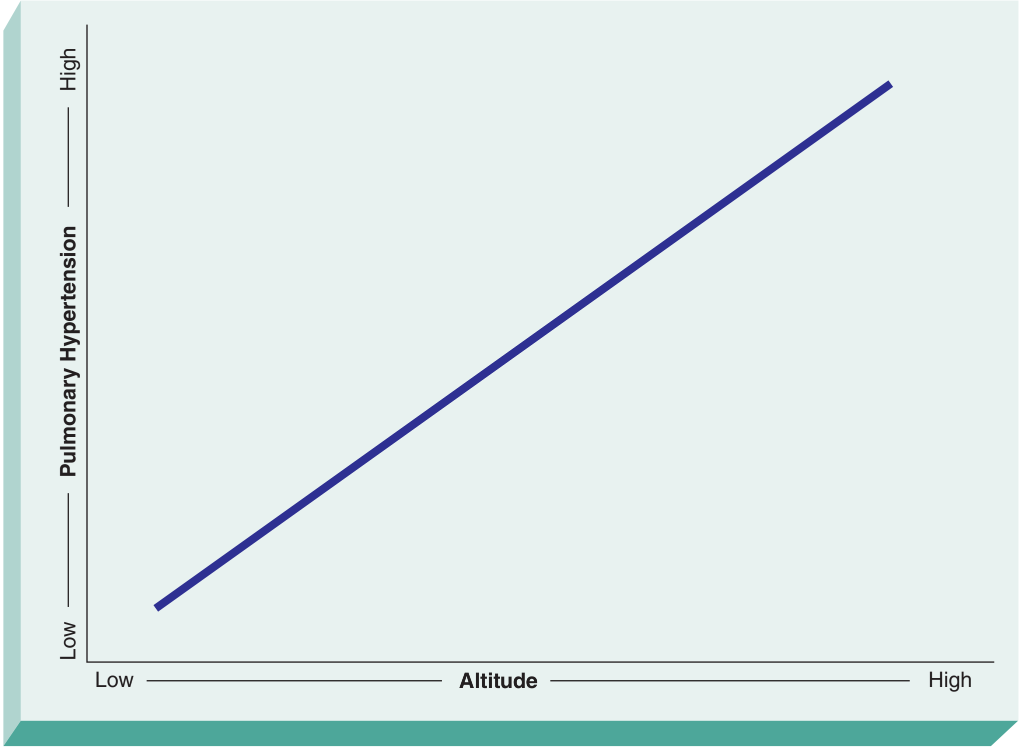
As an individual ascends from the Earth's surface, pulmonary hypertension progressively increases as a result of *hypoxic pulmonary vasoconstriction*. A linear relationship exists between the degree of ascent and the degree of pulmonary vasoconstriction and hypertension (Figure 19–4). The exact mechanism of this phenomenon is unclear. It is known, however, that it is the partial pressure of oxygen in the alveoli, not the partial pressure of arterial oxygen, that chiefly controls this response.

Other Physiologic Changes

Sleep Disorders

During the first few days at high altitude, lowlanders frequently awaken during the night and complain that they do not feel refreshed when they awake in the morning. When sleeping, they commonly demonstrate breathing that waxes and wanes with apneic periods of 10- to 15-second duration (Cheyne-Stokes respiration). The arterial oxygen saturation (Sa_{O_2}) fluctuates accordingly.

FIGURE 19-4 Pulmonary hypertension increases linearly as altitude increases.



Clinical Connection 19-1

Hypobaric Sleep and the Athlete in Training[2]

An interesting phenomenon occurring in elite athletes is the linking of sleep to athletic performance (Figure 19–5). Obviously, sleep is important to all individuals as a restorative time, but some elite athletes are utilizing the sleep period as an additional means to maximize performance. One such innovation is the use of **hypobaric,** or **high altitude, chambers** for sleep. In essence, hypobaric sleep chambers mimic the effects of high altitude by producing a sleep environment that has pressures less than sea-level—that is, the same barometric pressures that are found at altitudes greater than sea

FIGURE 19-5 Elite athlete training at high altitudes.

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(Continued)

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[2] Also see related Clinical Connection 4–2: Hyperbaric Oxygen Therapy—A clinical Application of Henry's law, and Clinical Connection 6–9: Blood Doping.

Clinical Connection 19-1, Continued

level. Regulated airflow in and out of the chamber is maintained to allow for fresh oxygen and the evacuation of carbon dioxide.

At increased altitudes—those greater than sea level—the barometric pressure is reduced in proportion to the increase in altitude. Recall that barometric pressure progressively decreases at higher altitudes (see Figure 2–4). Although oxygen is still present at 21 percent—room air equivalent—the decrease in overall barometric pressure means an overall decrease in the partial pressure of inspired oxygen. Hypobaric chambers can simulate altitudes of up to 14,500 feet, which is a barometric pressure equivalent of about 451 mm Hg. This means the partial pressure of atmospheric oxygen in the sleep chamber is only about 95 mm Hg. (Recall that at sea level, the barometric pressure is about 760 mm Hg, and the oxygen pressure is about 160 mm Hg.)

The decrease in the partial pressure of inspired oxygen in the chamber exposes the individual to a relative level of hypoxemia equivalent to the overall decrease in inspired oxygen. The higher the altitude that is being mimicked, the lower the inspired oxygen and, consequently, the more hypoxemia that is experienced.

What is the benefit of inducing hypoxemia to the sleeping athlete? In short, how might the athlete gain a competitive advantage? The general rationale for this type of training is this: Hypoxemia is a stimulus for the increased production of **erythropoietin,** which in turn stimulates the production of more red blood cells. Theoretically, by increasing the red blood cell production, the athlete can increase oxygen delivery to working muscles during competition—which in turn should enhance overall athletic performance. The hypobaric chamber offers a means to obtain the benefits of altitude training, without the travel and other inconveniences. Thus, the athletes can "live high" during sleep and "train low" while working out at atmospheric pressures in their own environments.

Myoglobin Concentration

The concentration of myoglobin in skeletal muscles is increased in high-altitude natives, and studies of this group have shown a high concentration of myoglobin in the diaphragm, the adductor muscles of the leg, the pectoral muscles, and the myocardium. Myoglobin enhances the transfer of oxygen between the capillary blood and peripheral cells, buffers regional P_{O_2} differences, and provides an oxygen storage compartment for short periods of very severe oxygen deprivation.

Acute Mountain Sickness

Newcomers to high altitude frequently experience what is known as **acute mountain sickness,** which is characterized by headache, fatigue, dizziness, palpitation, nausea, loss of appetite, and insomnia. Symptoms usually do not occur until 6 to 12 hours after an individual ascends to a high altitude. The symptoms are generally most severe on the second or third day after ascent. Acclimatization is usually complete by the fourth or fifth day.

The precise cause of acute mountain sickness is not known. It is suggested that the primary cause is hypoxia, complicated by the hypocapnia and respiratory alkalosis associated with high altitude. It may also be linked to a fluid imbalance because pulmonary edema, cerebral edema, and peripheral edema are commonly associated with acute and chronic mountain sickness.

Sensitivity to acute mountain sickness varies greatly among individuals. Being physically fit is no guarantee of immunity. Younger people appear to be more at risk. In some cases, descent to a lower altitude may be the only way to reduce the symptoms.

High-Altitude Pulmonary Edema

High-altitude pulmonary edema is sometimes seen in individuals with acute mountain sickness. A typical scenario is as follows: A lowlander rapidly ascends to a high altitude and is very active during the trip or upon arrival. Initially, the lowlander demonstrates shortness of breath, fatigue, and a dry cough. Physical signs include tachypnea, tachycardia, and crackles at the lung bases. Orthopnea is commonly present at this time. In severe cases, the lowlander may cough up large amounts of pink, frothy sputum. Death may occur.

The exact cause of high-altitude pulmonary edema is not fully understood. It may be associated with the pulmonary vasoconstriction that occurs in response to the alveolar hypoxia. It may also be associated with an increased permeability of the pulmonary capillaries. The best treatment of high-altitude pulmonary edema is rapid descent. Oxygen therapy should be administered.

High-Altitude Cerebral Edema

High-altitude cerebral edema is a serious complication of acute mountain sickness. It is characterized by photophobia, ataxia, hallucinations, clouding of consciousness, coma, and possibly death. The precise cause of high-altitude cerebral edema is unclear. It is suggested that it may be linked to the increased cerebral vasodilation and blood flow that result from hypoxia. Oxygen therapy should be administered if available.

Chronic Mountain Sickness

Chronic mountain sickness (also known as Monge's disease) is sometimes seen in long-term residents at high altitude. It is characterized by fatigue, reduced exercise tolerance, headache, dizziness, somnolence, loss of mental acuity, marked polycythemia, and severe hypoxemia. The severe oxygen desaturation and polycythemia cause a cyanotic appearance. A hematocrit of 83 percent and hemoglobin concentrations as high as 28 g/dL have been reported. As a result of the high hematocrit, the viscosity of the blood is significantly increased. Right ventricular hypertrophy is common.

Chapter Summary

A basic knowledge of the effects of high altitude on the cardiopulmonary system can enhance the respiratory care practitioner's understanding of how chronic oxygen deprivation can be applied to the treatment of chronic hypoxia caused by lung disease. Major cardiopulmonary changes seen after a period of acclimatization at high altitude include increased ventilation, polycythemia, acid–base balance changes, an increased oxygen diffusion capacity, an increased alveolar-arterial P_{O_2} difference, and an overall improved ventilation-perfusion ratio. Long-term exposure to high altitude does not change an individual's cardiac output but does cause pulmonary hypertension. Finally, high altitudes disrupt normal sleep patterns; increase myoglobin in the skeletal muscles; and can cause acute or chronic mountain sickness, pulmonary edema, and cerebral edema. The clinical connection associated with these topics discusses hypobaric sleep and athlete training.

Review Questions

1. The barometric pressure is about half the sea-level value of 760 mm Hg at an altitude of
   A. 4,000–5,000 feet
   B. 9,000–10,000 feet
   C. 14,000–15,000 feet
   D. 18,000–19,000 feet

2. The oxygen diffusion capacity of high-altitude natives is about
   A. 5–10 percent greater than predicted
   B. 10–15 percent greater than predicted
   C. 15–20 percent greater than predicted
   D. 20–25 percent greater than predicted

3. Acute mountain sickness is characterized by
   1. Sleep disorders
   2. Headache
   3. Dizziness
   4. Palpitation
   5. Loss of appetite
      A. 1 and 3 only
      B. 2 and 4 only
      C. 1, 4, and 5 only
      D. 1, 2, 3, 4, and 5

4. The symptoms of acute mountain sickness are generally most severe on the
   A. First or second day after ascent
   B. Second or third day after ascent
   C. Third or fourth day after ascent
   D. Fourth or fifth day after ascent

5. When an individual is subjected to a high altitude for a prolonged period of time, which of the following is(are) seen?
   1. An increased red blood cell production
   2. A decreased Pa_{CO_2}
   3. An increased $P_{(A-a)O_2}$
   4. A decreased alveolar ventilation
      A. 1 and 3 only
      B. 2 and 4 only
      C. 3 and 4 only
      D. 1, 2, and 3 only

6. At high altitude, the overall ventilation–perfusion ratio improves. True _____ False _____

7. In individuals who have acclimatized to a high altitude, an increased cardiac output is seen. True _____ False _____

8. There is a linear relationship between the degree of ascent and the degree of pulmonary vasoconstriction and hypertension. True _____ False _____

9. Natives who have been at high altitudes for generations commonly demonstrate a mild respiratory alkalosis. True _____ False _____

10. The concentration of myoglobin in skeletal muscles is decreased in high-altitude natives. True _____ False _____

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CHAPTER 20

High-Pressure Environments and Their Effects on the Cardiopulmonary System

OBJECTIVES

By the end of this chapter, the student should be able to:

1. Describe the effects of a high-pressure environment on the cardiopulmonary system.
2. Explain the effects of diving on the cardiovascular system.
3. Discuss the therapeutic uses of hyperbaric medicine.

Introduction

High-pressure environments have a profound effect on the cardiopulmonary system. Such environments are encountered in recreational scuba diving, deep sea diving, and hyperbaric medicine. The effects of high-pressure environments on the cardiopulmonary system are typically studied in (1) actual dives in the sea; (2) hyperbaric chambers, where the subject is exposed to mixtures of compressed gases (known as "simulated dry dives"); and (3) a water-filled hyperbaric chamber that can simulate any depth by adjusting the gas pressure above the water (known as "simulated wet dives").

Diving

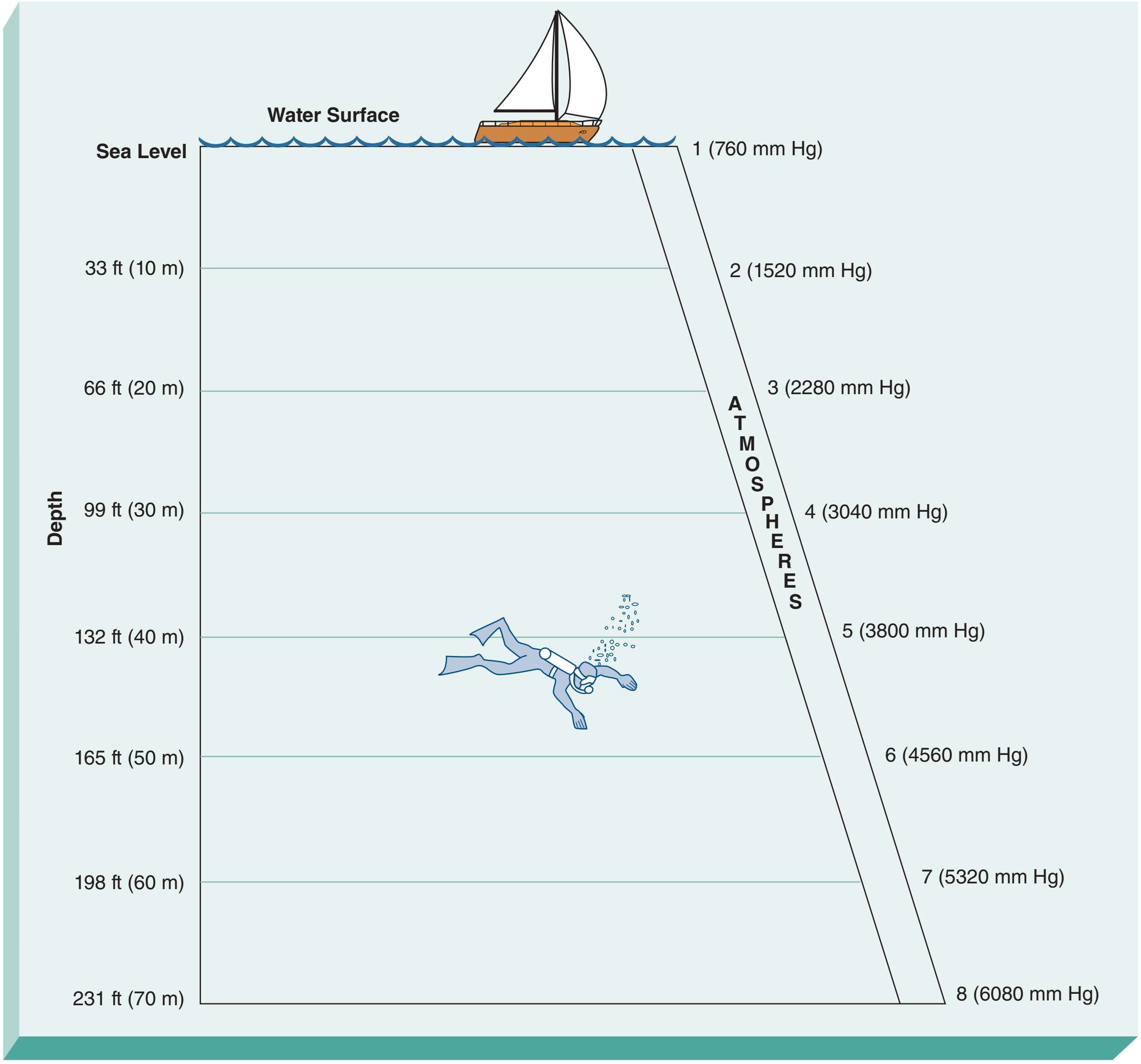
Because water is incompressible, the pressure increases linearly with depth. For every 33 feet (10 meters) below the surface, the pressure increases 1.0 atmosphere (760 mm Hg). Thus, the total pressure at a depth of 33 feet is 2 atmospheres (1520 mm Hg)—1.0 atmosphere (1 atm) owing to the water column and 1.0 atmosphere pressure owing to the gaseous atmosphere above the water. At 66 feet (20 meters) below the surface, the pressure is 3.0 atmospheres (2280 mm Hg) (Figure 20–1).

As an individual descends into water, the lung is compressed according to Boyle's law:

$$P_1 \times V_1 = P_2 \times V_2$$

where P_1 is the pressure prior to the dive, V_1 is the lung volume prior to the dive, P_2 is the pressure generated at a specific water depth, and V_2 is the lung volume at that water depth.

FIGURE 20-1 Pressure increases linearly with depth. For every 33 feet (10 meters) below sea level, the pressure increases 1.0 atmosphere (atm). The depth in feet below sea water is referred to as *feet of sea water* (FSW).


Water Surface
Sea Level
1 (760 mm Hg)
33 ft (10 m)
2 (1520 mm Hg)
66 ft (20 m)
3 (2280 mm Hg)
ATMOSPHERES
99 ft (30 m)
4 (3040 mm Hg)
Depth
132 ft (40 m)
5 (3800 mm Hg)
165 ft (50 m)
6 (4560 mm Hg)
198 ft (60 m)
7 (5320 mm Hg)
231 ft (70 m)
8 (6080 mm Hg)

Thus, if an individual fully inhales to a total lung capacity of 6 L at sea level, and dives to a depth of 33 feet, the lungs will be compressed to about 3 L:

$$
\begin{aligned}
V_2 &= \frac{P_1 \times V_1}{P_2} \\
&= \frac{1 \times 6}{2} \\
&= 3 \text{ L}
\end{aligned}
$$

At 66 feet, the lungs would be compressed to about 2 L. At 99 feet, the lungs would be compressed to about 1.5 L.

Boyle's law can also be used to calculate the pressure within a diver's lungs at a specific depth. For example, when the previously mentioned diver descends from sea level to a depth of 33 feet (compressing the lung volume from 6 to 3 L), the pressure within the diver's lungs will increase from 760 mm Hg to about 1520 mm Hg:

$$\begin{aligned} P_2 &= \frac{P_1 \times V_1}{V_2} \\ &= \frac{760 \times 6}{3} \\ &= 1520 \text{ mm Hg} \end{aligned}$$

At 66 feet, the pressure within a diver's lungs will be about 2280 mm Hg. At 99 feet, the pressure will be about 3040 mm Hg.

Breath-Hold Diving

Breath-hold diving is the simplest and most popular form of diving. The maximum duration of a breath-hold dive is a function of (1) the diver's metabolic rate and (2) the diver's ability to store and transport O_2 and CO_2. A delicate balance exists between the diver's O_2 and CO_2 levels during a breath-hold dive. For example, the P_{CO_2} must not rise too rapidly and reach the so-called respiratory drive **breaking point** (generally about 55 mm Hg) before the diver returns to the surface. On the other hand, the diver's P_{CO_2} must rise fast enough (relative to the decrease in O_2) to alert the diver of the need to return to the surface before hypoxia-induced loss of consciousness occurs.

Clinical Connection 20-1

Guinness World Record for Breath-Holding

On April 30, 2008, magician David Blaine set the world record for the longest breath-holding, by holding his breath for 17 minutes and 4.4 seconds, during a live telecast of *The Oprah Winfrey Show* in Chicago.[1] Blaine spent 23 minutes inhaling pure oxygen, packing his lungs with extra oxygen just before the breathing tubes were removed in a sphere filled with 1800 gallons of water. Up to 30 minutes of so-called oxygen hyperventilation is allowed under the Guinness guidelines.

The reader is challenged to consider the following: Assuming an average total lung capacity, approximately how much oxygen did Mr. Blaine have in his lungs for the record breath-hold? (Remember from Chapter 6 that the average person consumes about 250 mL of oxygen per minute.) How fast was his heart rate during this event? What was the impact of a rapid heart rate on Mr. Blaine's oxygen consumption? What were his Pa_{CO_2} and pH levels at the end of this event?

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[1] See YouTube presentation of David Blain setting the world record for the longest breath-holding on *The Oprah Winfrey Show*, which aired April 30, 2008:
Part 1: https://www.youtube.com/watch?v=upNRJJOcxR8.
Part 2: https://www.youtube.com/watch?v=olKlc4Bv6CA.

Voluntary hyperventilation can prolong the duration of a breath-hold dive. Hyperventilation reduces the diver's CO_2 stores and, therefore, increases the time before the CO_2 stores are replenished and the breaking point is reached. Note, however, that hyperventilation prior to a breath-hold dive can be dangerous. The diver's oxygen stores may fall to a critically low level before the CO_2 breaking point is reached. Should this happen, the diver could lose consciousness before reaching the surface and drown.

The CO_2–O_2 Paradox

When an individual breath-hold dives to a great depth, a so-called paradoxical reversal occurs in the flow of CO_2 and O_2 between the alveoli and the pulmonary capillary blood. This **CO_2–O_2 paradox** is caused by the pressure changes that develop around the diver's body during the dive. The CO_2 paradox occurs as the diver descends, and the O_2 paradox occurs as the diver ascends.

The reason for the CO_2 paradox is as follows: As the diver descends, the lungs are compressed and the pressure in the lungs increases. In fact, the gas pressure in the lungs is about doubled when the diver reaches a depth of 33 feet (2 atm). Thus, assuming a normal $P_{A_{O_2}}$ of about 100 mm Hg and $P_{A_{CO_2}}$ of about 40 mm Hg, at a depth of 33 feet, the $P_{A_{O_2}}$ will be about 200 mm Hg and the $P_{A_{CO_2}}$ will be about 80 mm Hg.

In view of these pressure increases, it can be seen that as a diver progressively descends, a CO_2 paradox will occur when the $P_{A_{CO_2}}$ becomes greater than the $P\bar{v}_{CO_2}$ of the pulmonary capillary blood (normally about 46 mm Hg). In other words, the CO_2 in the alveoli will move into the pulmonary capillary blood. As the diver returns to the surface, the alveolar air expands, causing the $P_{A_{CO_2}}$ to decrease. When this happens, the CO_2 from the pulmonary capillary blood will again move into the alveoli. It is suggested that this mechanism might work to relieve the respiratory CO_2 drive (breaking point) as the diver moves toward the surface.

The reason for the O_2 paradox is as follows: Like the $P_{A_{CO_2}}$, the $P_{A_{O_2}}$ increases as the diver descends, causing more O_2 to move from the alveoli into the pulmonary capillary blood. This mechanism provides more dissolved O_2 for tissue metabolism. However, this physiologic advantage is lost as the diver returns to the surface and as the lungs expand and the $P_{A_{O_2}}$ decreases. If a good portion of the O_2 is taken up from the lungs during descent, the $P_{A_{O_2}}$ decline during ascent may be significant. In fact, $P_{A_{O_2}}$ can fall below the $P\bar{v}_{O_2}$ of the pulmonary capillary blood. When this happens, the O_2 paradox occurs. That is, the O_2 in the pulmonary capillary blood moves into the alveoli. The fall in $P_{A_{O_2}}$ as a diver returns to the surface is also known as the **hypoxia of ascent**.

The Mammalian Diving Reflex

The **mammalian diving reflex** (also known as *diving reflex* or *diving response*) consists of bradycardia, decreased cardiac output, lactate accumulation in underperfused muscles, and peripheral vasoconstriction elicited during a breath-hold deep dive. The mammalian diving reflex is a set of physiologic reflexes that acts as the first line of defense against hypoxia. The diving reflex may partially explain the survival of numerous near-drowning cases in cold water after submersion lasting more than 40 minutes. It is suggested that the peripheral vasoconstriction elicited during a deep dive conserves oxygen for the heart and central nervous system by shunting blood away from less vital tissues.

Decompression Sickness

During a deep dive, the dissolved nitrogen in the diver's blood will move into body tissues. The amount of dissolved gas that enters the tissues is a function of (1) the solubility of the gas in the tissues, (2) the partial pressure of the gas, and (3) the hydrostatic pressure in the tissue.

During ascent (decompression), the pressure around the diver's body falls, reducing the hydrostatic pressure in the tissues and, therefore, the ability of the tissues to hold inert gases. When the decompression is performed at an appropriately slow rate, the gases leaving the tissues will be transported (in their dissolved state) by the venous blood to the lungs and exhaled. When the decompression is conducted too rapidly, the gases will be released from the tissue as bubbles. Depending on the size, number, and location of the bubbles, they can cause a number of signs and symptoms, collectively referred to as **decompression sickness**. Decompression sickness includes, but is not limited to, joint pains (the bends), chest pain and coughing (the chokes), paresthesia and paralysis (spinal cord involvement), circulatory failure and, in severe cases, death.

Barotrauma

While diving, the increased pressure can cause tissue injury in the lungs, middle ear, paranasal sinuses, and gastrointestinal tract. Middle-ear barotrauma is the most common diving-related disorder encountered by divers. Barotrauma can occur in the alveoli distal to a blocked airway, in a paranasal sinus with an obstructed orifice, in a small pocket of air left between a tooth filling and the base of the tooth, or in the air space within a diving mask (mask squeeze). Facial edema, ecchymoses (bluish discoloration of an area of skin), and conjunctival hemorrhages are often observed after diving. Gastrointestinal barotrauma may also occur when air enters the stomach as a result of a faulty breathing apparatus or by swallowing air. On ascent, the expanding gas can distend the stomach or intestine. In extreme cases, an overextended stomach may rupture and lead to a condition known as pneumoperitoneum (air in the peritoneal cavity of the abdomen).

Hyperbaric Medicine

The administration of oxygen at increased ambient pressures is now being used routinely to treat a variety of pathologic conditions. Clinically, this therapy is referred to as **hyperbaric medicine** and is accomplished by means of a hyperbaric chamber. Most of the therapeutic benefits of hyperbaric oxygenation are associated with the increased oxygen delivery to the tissues.

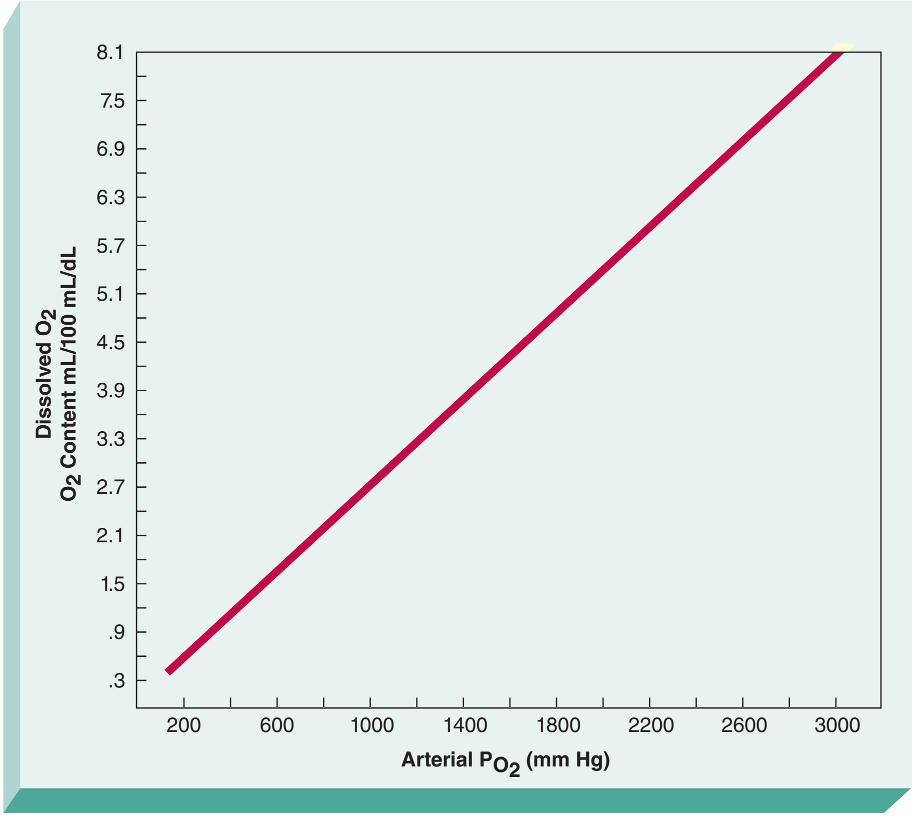
As discussed in Chapter 6, hemoglobin is about 97 percent saturated with oxygen at a normal arterial P_{O_2} of 80 to 100 mm Hg. Very little additional O_2 can be combined with hemoglobin once this saturation level is reached. However, the quantity of dissolved O_2 will continue to rise linearly as the Pa_{O_2} increases. Approximately 0.3 mL of O_2 physically dissolves in each 100 mL of blood for every Pa_{O_2} increase of 100 mm Hg (Figure 20–2).

Clinical Connection 20-2

Glossopharyngeal Insufflation

Glossopharyngeal insufflation (GI)—also called **lung packing** or **buccal pumping**—is a technique used by competitive breath-hold divers to enhance their diving performance. The breath-hold diver uses the oropharyngeal musculature to pump boluses of air into the lungs to increase the volume above his or her normal total lung capacity. Breath-hold divers use GI to help prevent lung compression at great water depth and to increase the volume of oxygen in the lungs—thus, increasing breath-hold time. Although the experienced breath-hold diver can increase their lung volumes by up to 3 L, this maneuver is associated with hypotension, decreased cardiac output, pulmonary barotrauma, and pneumomediastinum.

FIGURE 20-2 The quantity of dissolved O_2 increases linearly as the Pa_{O_2} increases. About 0.3 mL of O_2 physically dissolves in each 100 mL of blood for every 100 mm Hg increase in Pa_{O_2}.



Indications for Hyperbaric Oxygenation

As shown in Table 20–1, the administration of hyperbaric oxygen is now indicated for a number of clinical conditions. Hyperbaric oxygen has long been useful in the treatment of diseases such as decompression sickness and gas embolism. Regardless of the cause of the bubbles, hyperbaric oxygen is effective in reducing bubble size, accelerating bubble resolution, and maintaining tissue oxygenation.

Hyperbaric oxygen is used empirically to enhance wound healing in conditions associated with ischemic hypoxia. Clinically, such conditions include radiation necrosis of bone or soft tissue, diabetic microangiopathy, compromised skin grafts, crush wounds, acute traumatic ischemias, and thermal burns. For these conditions, it appears that hyperbaric oxygen increases both the tissue oxygenation and capillary density.

Clinical evidence supports the use of hyperbaric oxygen for the treatment of anaerobic infections, including clostridial myonecrosis (gas gangrene); a variety of necrotizing soft-tissue infections; and chronic refractory osteomyelitis. Hyperbaric oxygen added to surgery and antibiotics in the treatment of clostridial myonecrosis increases tissue salvage and decreases mortality.

Hyperbaric oxygen is effective in the treatment of carbon monoxide poisoning. Carbon monoxide poisoning, which is caused by all sources of combustion (such as defective indoor heaters, automobile exhaust systems, or smoke inhalation), is the leading cause of death by poisoning in the United States. The severity of intoxication is a function of both the level and duration of carbon monoxide exposure. The administration of hyperbaric oxygen (1) increases the physically dissolved O_2 in the arterial blood by as much as 5 mL/dL O_2, (2) increases the pressure gradient for driving oxygen into ischemic tissues, and (3) reduces the half-life of **carboxyhemoglobin** (CO_{Hb}). The CO_{Hb} half-life when a victim is breathing room

TABLE 20-1 Indications for Hyperbaric Oxygenation

Indications for Hyperbaric Oxygenation
Gas Disorders • Decompression sickness • Gas embolism
Vascular Disorders • Radiation necrosis • Diabetic microangiopathy • Nonhealing skin grafts • Crush injuries • Acute traumatic ischemias • Thermal burns
Infections • Clostridial gangrene • Necrotizing soft-tissue infections (flesh-eating bacteria) • Refractory osteomyelitis
Oxygen Transport Disorders • Carbon monoxide (CO) poisoning • Severe anemia or blood loss

air at 1 atm is approximately 5 hours. That is, a CO_{Hb} of 20 percent will decrease to about 10 percent in 5 hours and 5 percent after another 5 hours. Breathing 100 percent oxygen at 1 atm reduces the CO_{Hb} half-life to less than 1 hour.

Hyperbaric oxygen therapy is generally a safe procedure, and complications are rare. Potential risks include temporary myopia (nearsightedness), middle ear injuries (e.g., eardrum rupture caused by increased air pressure), lung collapse caused by air pressure changes, and seizures.

Chapter Summary

High-pressure environments have a profound effect on the cardiopulmonary system. Important topics in this area include scuba diving, breath-hold diving, the CO_2–O_2 paradox, the mammalian diving reflex, barotrauma, and decompression sickness. Currently, the administration of hyperbaric oxygen is being used routinely to treat a variety of pathologic conditions, including gas diseases (e.g., decompression sickness), vascular insufficiency states (e.g., compromised skin grafts, thermal burns), infections (e.g., clostridial myonecrosis), and defects in oxygen transport (e.g., carbon monoxide poisoning). Clinical connections associated with these topics include the world record for breath-holding and glossopharyngeal insufflation.

Review Questions

1. At what depth below the water surface does the pressure increase to 3.0 atm?

A. 33 feet
B. 66 feet
C. 99 feet
D. 132 feet

2. If an individual fully inhales to a total lung capacity of 4.5 L at sea level (760 mm Hg) and dives to a depth of 66 feet, the lungs will be compressed to about

A. 1.0 L
B. 1.5 L
C. 2.0 L
D. 2.5 L

3. At sea level, a diver has the following:

- Lung volume: 6 L
- Pressure within the lungs: 755 mm Hg

If this individual dives to a depth of 99 feet and compresses the lung volume to 2 L, what will be the pressure within the diver's lungs?

A. 960 mm Hg
B. 1420 mm Hg
C. 1765 mm Hg
D. 2265 mm Hg

4. The diving reflex consists of

1. Tachycardia
2. Decreased cardiac output
3. Bradycardia
4. Peripheral vasoconstriction
    A. 2 only
    B. 3 and 4 only
    C. 1 and 3 only
    D. 2, 3, and 4 only

5. The half-life of carboxyhemoglobin (CO_{Hb}) when a victim is breathing room air at 1 atm is approximately

A. 2 hours
B. 3 hours
C. 4 hours
D. 5 hours

6. Hyperventilation prior to a breath-hold dive can be dangerous. True _____ False _____

7. The fall in $P_{A_{O_2}}$ as a diver returns to the surface is known as the hypoxia of ascent. True _____ False _____

8. Chest pain and coughing caused by decompression sickness is known as the bends. True _____ False _____

9. The so-called P_{CO_2} respiratory drive breaking point during a dive is about 55 mm Hg. True _____ False _____

10. Approximately 0.3 mL of O_2 is physically dissolved in each 100 mL of blood for every Pa_{O_2} increase of 100 mm Hg. True _____ False _____

Glossary

A

Abduct to draw away from the median plane of the body or from one of its parts.

Absolute shunt the sum of the anatomic and capillary shunts is referred to as *true* or *absolute shunt*. Absolute shunting is refractory to oxygen therapy.

Acclimatization physiologic or psychologic adjustment to a new environment.

Acetylcholine a chemical found in most organs and tissues. Acetylcholine plays an important role in the transmission of parasympathetic nerve impulses at the synapses.

Acid a compound that yields hydrogen ions when dissociated in aqueous solution (Arrhenius definition) or acts as a hydrogen ion donor (Brønsted definition) or acts as an electron pair acceptor (Lewis definition). Acids turn blue litmus red, have a sour taste, and react with bases to form salts. Acids have chemical properties essentially the opposite to those of bases.

Acidemia a decrease in the arterial blood pH below 7.35. The hydrogen ion concentration of the blood increases as reflected by a lowering of serum pH values.

Acidosis (*adj. acidotic*) an abnormal increase in hydrogen ion concentration in the body, resulting from an accumulation of an acid or the loss of a base. It is indicated by a blood pH below the normal range (7.35 to 7.45). The various forms of acidosis are named for their cause; for example, renal tubular acidosis results from failure of the kidney to secrete hydrogen ions or reabsorb bicarbonate ions, respiratory acidosis results from respiratory retention of CO_2, and diabetic acidosis results from an accumulation of ketones associated with lack of insulin. Treatment depends on diagnosis of the underlying abnormality and concurrent correction of the acid–base imbalance. Compare **alkalosis**.

Acinus (*pl. acini*) any small saclike structure, particularly one found in a gland. A subdivision of the lung consisting of the tissue distal to a terminal bronchiole.

Acromion process lateral portion of the spine of the scapula that forms the point of the shoulder. It articulates with the clavicle and gives attachment to the deltoid and trapezius muscles.

Action potential an electrical impulse consisting of a self-propagating series of polarizations and depolarizations, transmitted across the plasma membranes of a nerve fiber during the transmission of a nerve impulse and across the plasma membranes of a muscle cell during contraction or other activity. In the absence of an impulse, the inside is electrically negative and the outside is positive (the resting potential). During the passage of an impulse at any point on the nerve fiber, the inside becomes positive and the outside, negative. Also called *action current*.

Acute beginning abruptly with marked intensity or sharpness, then subsiding after a relatively short period. Compare **chronic**.

Acute alveolar hyperventilation a condition marked by low levels of carbon dioxide, and a high pH in the blood, due to breathing excessively. Also called respiratory alkalosis.

Acute epiglottitis a severe, rapidly progressing bacterial infection of the upper respiratory tract that occurs in young children, primarily between 2 and 7 years of age. It is characterized by sore throat, croupy stridor, and inflamed epiglottis, which may cause sudden respiratory obstruction and possibly death. The infection is generally caused by *Haemophilus influenzae*, type B, although streptococci may occasionally be the causative agent. Transmission occurs by infection with airborne particles or contact with infected secretions. The diagnosis is made by bacteriologic identification of *H. influenzae*, type B, in a specimen taken from the upper respiratory tract or in the blood. A lateral X-ray film of the neck shows an enlarged epiglottis and distention of the hypopharynx, which distinguishes the condition from croup. Direct visualization of the inflamed, cherry-red epiglottis by depression of the tongue or indirect laryngoscopy is also diagnostic but may produce total acute obstruction and should be attempted only by trained personnel with equipment to establish an airway or to provide respiratory resuscitation, if necessary. Compare **croup**.

Acute respiratory distress syndrome a severe pulmonary congestion characterized by diffuse injury to alveolar-capillary membranes. Fulminating sepsis, especially when gram-negative bacteria are involved, is the most common cause. ARDS may occur after trauma; near-drowning; aspiration of gastric acid; paraquat ingestion; inhalation of corrosive chemicals, such as chlorine, ammonia, or phosgene; or the use of certain drugs, including barbiturates, chlordiazepoxide, heroin, methadone hydrochloride, propoxyphene hydrochloride, and salicylates. Other causes include diabetic ketoacidosis, fungal infections, high altitude, pancreatitis, tuberculosis, and uremia. Also called adult respiratory distress syndrome, congestive atelectasis, hemorrhagic lung, noncardiogenic pulmonary edema, pump lung, shock lung, stiff lung, wet lung.

Acute ventilatory failure with partial renal compensation a condition marked by high levels of carbon dioxide and a low pH in the blood resulting from hypoventilation, which is partly corrected by the retention of HCO_3^- via the renal system and/or the administration of HCO_3^-.

Adenoid one of two masses of lymphatic tissue situated on the posterior wall of the nasopharynx behind the posterior nares. During childhood these masses often swell and block the passage of air from the nasal cavity into the pharynx, preventing the child from breathing through the nose. Also called pharyngeal tonsils.

Adrenergic nerve fibers that, when stimulated, release epinephrine at their endings. Adrenergic fibers include nearly all sympathetic postganglionic fibers except those innervating sweat glands.

Adrenergic receptors a site in a sympathetic effector cell that reacts to adrenergic stimulation. Two types of adrenergic receptors are recognized: alpha-adrenergic, which act in response to sympathomimetic stimuli, and beta-adrenergic, which block sympathomimetic activity. In general, stimulation of alpha receptors is excitatory of the function of the host organ or tissue, and stimulation of the beta receptors is inhibitory.

Afferent carrying impulses toward a center.

Afferent nerves nerves that carry impulses from the periphery to the central nervous system.

Affinity attraction between two substances that, when united, form new substances (i.e., oxygen and hemoglobin form oxyhemoglobin).

Agranulocyte any leukocyte that does not contain predominant cytoplasmic granules, such as a monocyte or lymphocyte.

Air trapping the prevention of gas from leaving the alveoli during exhalation. This is usually caused by airway closure during exhalation.

Airway resistance a measure of the impedance to airflow through the bronchopulmonary system. Calculated by the pressure difference between the mouth and alveoli divided by flow rate.

Alar cartilage refers to the greater alar cartilage (lower lateral cartilage), which is a thin, flexible plate, situated immediately below the lateral nasal cartilage and bent upon itself in such a manner as to form the medial wall and lateral wall of the naris of its own side.

Alkalemia an increase in the arterial blood pH above 7.45 due to a decrease in the hydrogen ion concentration or an increase in hydroxyl ions.

Alkalosis an abnormal condition of body fluids, characterized by a tendency toward a blood pH level greater than 7.45, for example, from an excess of alkaline bicarbonate or a deficiency of acid. Respiratory alkalosis may be caused by hyperventilation, resulting from an excess loss of carbon dioxide and a carbonic acid deficit. Metabolic alkalosis may result from an excess intake or retention of bicarbonate, loss of gastric acid in vomiting, potassium depletion, or any stimulus that increases the rate of sodium-hydrogen exchange. When a buffer system, such as carbon dioxide retention or bicarbonate excretion, prevents a shift in pH, it is labeled compensating alkalosis. Treatment of uncompensated alkalosis involves correction of dehydration and various ionic deficits to restore the normal acid-base balance in which the ratio of carbonic acid to bicarbonate is 20:1. Compare **acidosis**.

Allergen any substance that causes an allergic reaction. It may or may not be a protein.

Allergy a hypersensitive reaction to common, often intrinsically harmless substances, most of which are environmental.

Alpha receptor any of the postulated adrenergic components of receptor tissues that respond to norepinephrine and to various blocking agents. The activation of the alpha receptors causes such physiologic responses as increased peripheral vascular resistance, dilation of the pupils, and contraction of pilomotor muscles. Also called *alpha-adrenergic receptor*. Compare **beta receptor**.

Alveolar hyperventilation with partial renal compensation a condition marked by low levels of carbon dioxide and a high pH in the blood due to hyperventilation, which is partly corrected by the excretion of HCO_3^- via the renal system.

Alveolar sac an air sac at one of the terminal cavities of lung tissue.

Alveolus a small outpouching of walls of alveolar space through which gas exchange between alveolar air and pulmonary capillary blood takes place. The term is often used interchangeably with acinus. See also **alveolar sac**, **pulmonary alveolus**.

Amniocentesis an obstetric procedure in which a small amount of amniotic fluid is removed for laboratory analysis. It is usually performed between the sixteenth and twentieth weeks of gestation to aid in the diagnosis of fetal abnormalities, especially genetic disorders.

Amniotic fluid liquid produced by the fetal membranes and the fetus; it surrounds the fetus throughout pregnancy, usually totaling about 1000 mL at term.

Anaerobic threshold the point at which the level of exercise is greater than the ability of the cardiopulmonary system to provide a sufficient supply of oxygen to the muscles, causing anaerobic metabolism to ensue.

Analogous similar in function but having a different origin or structure.

Anastomosis joining of vessels, either naturally or surgically, to allow flow to other structures.

Anatomic shunt an anatomic shunt (also called a *true shunt*) exists when blood flows from the right side of the heart to the left side without coming in contact with an alveolus for gas exchange. In the healthy lung, there is a normal anatomic shunt of about 3 percent of the cardiac output. This normal shunting is caused by nonoxygenated blood completely bypassing the alveoli and entering (1) the pulmonary vascular system by means of the bronchial venous drainage and (2) the left atrium by way of the thebesian veins. Common abnormalities that cause anatomic shunting include congenital heart disease, intrapulmonary fistula, and vascular lung tumors.

Anemia disorder characterized by a decrease in hemoglobin in the blood to levels below the normal range.

Anemic hypoxia a type of hypoxia in which the oxygen tension in the arterial blood is normal, but the oxygen-carrying capacity of the blood is inadequate. This form of hypoxia may develop from (1) a low amount of hemoglobin in the blood or (2) a deficiency in the ability of hemoglobin to carry oxygen, such as carbon monoxide poisoning.

Angiogram an x-ray film of an artery injected with a radiopaque contrast medium.

Anion gap the difference between primary measured cations (sodium Na^+ and potassium K^+) and the primary measured anions (chloride Cl^- and bicarbonate HCO_3^-) in serum. This test is most commonly performed in patients who present with altered mental status, unknown exposures, acute renal failure, and acute illnesses.

Anoxia an abnormal condition characterized by a local or systemic lack of oxygen in body tissues. It may result from an inadequate supply of oxygen to the respiratory system, an inability of the blood to carry oxygen to the tissues, or a failure of the tissues to absorb the oxygen from the blood.

Anterior indicating the front of a structure or body surface relative to other body parts.

Antibody protein substance that develops in response to and interacts with an antigen. The antigen–antibody reaction forms the basis of immunity.

Antigen substance that induces the formation of antibodies that interact specifically with it. The antigen-antibody reaction forms the basis for immunity.

Antitrypsin inhibitor of trypsin; may be deficient in persons with emphysema.

Aorta the main trunk of the systemic arterial circulation, comprising four parts: the ascending aorta, the arch of the aorta, the thoracic portion of the descending aorta, and the abdominal portion of the descending aorta.

Aortic arch the proximal one of the four portions of the aorta, giving rise to three arterial branches called the innominate (brachiocephalic), left common carotid, and left subclavian arteries. The arch rises at the level of the border of the second sternocostal articulation of the right side, passes to the left in front of the trachea, bends dorsally, and becomes the descending aorta. Also called the arch of the aorta.

Aperture opening or hole in an object or anatomic structure.

Apex top end or tip of a structure.

Apnea complete absence of spontaneous ventilation.

Apneustic center a portion of the pontine respiratory centers that influences the respiratory components of the medulla. If unrestrained, the apneustic center continually sends neural impulses to the ventral respiratory group and dorsal respiratory group in the medulla.

Arrhythmia any deviation from the normal pattern of the heartbeat.

Arterial pertaining to one artery or a network of arteries.

Arterial-venous oxygen content difference the differrence between the oxygen content of arterial blood (Ca_{O_2}) and the oxygen content of venous blood (Cv_{O_2}).

Arteriogram the reconstruction of blood vessels damaged by disease or injury, often performed by inflating a balloon within the vessel lumen at the site of narrowing to reconstitute flow.

Arteriole the smallest of the arteries. Blood flowing from the heart is pumped through the arteries, to the arterioles, to the capillaries, into the veins, and retuned to the heart. The muscular walls of the arterioles constrict and dilate in response to both local factors and neurochemical stimuli; thus, arterioles play a significant role in peripheral vascular resistance and in regulation of blood pressure.

Arteriosclerosis a common arterial disorder characterized by thickening, loss of elasticity, and calcification of arterial walls, resulting in a decreased blood supply.

Arteriovenous shunt a passageway, artificial or natural, that allows blood to flow from an artery to a vein without going through a capillary network.

Artery one of the large blood vessels carrying blood in a direction away from the heart.

Asphyxia severe hypoxia leading to hypoxemia and hypercapnia, loss of consciousness, and, if not corrected, death. Some of the more common causes of asphyxia are drowning, electrical shock, aspiration of vomitus, lodging of a foreign body in the respiratory tract, inhalation of toxic gas or smoke, and poisoning. Oxygen and artificial ventilation are promptly administered to prevent damage to the brain. The underlying cause is then treated.

Aspiration (1) drawing in or out by suction. (2) the act of withdrawing a fluid, such as mucus or serum, from the body by a suction device. See also **aspiration pneumonia**.

Aspiration pneumonia an inflammatory condition of the lungs and bronchi caused by the inhalation of foreign material or acidic vomitus.

Asthma a respiratory disorder characterized by recurring episodes of paroxysmal dyspnea, wheezing on expiration and/or inspiration caused by constriction of the bronchi, coughing, and viscous mucoid bronchial secretions. The episodes may be precipitated by inhalation of allergens or pollutants, infection, cold air, vigorous exercise, or emotional stress. Treatment may include elimination of the causative agent, hyposensitization, aerosol or oral bronchodilators, beta-adrenergic drugs, methylxanthines, cromolyn, leukotriene inhibitors, and short- or long-term use of corticosteroids.

Ataxia an abnormal condition characterized by impaired ability to coordinate movement.

Atelectasis an abnormal condition characterized by the collapse of alveoli, preventing the respiratory exchange of carbon dioxide and oxygen in a part of the lungs. Symptoms may include diminished breath sounds or aspiratory crackles, a mediastinal shift toward the side of the collapse, fever, and increasing dyspnea. The condition may be caused by obstruction of the major airways and bronchioles, by compression of the lungs as a result of fluid or air in the pleural space, or by pressure from a tumor outside the lung. Loss of functional lung tissue may secondarily cause increased heart rate, blood pressure, and respiratory rate. Secretions retained in the collapsed alveoli are rich in nutrients for bacterial growth, a condition often leading to stasis pneumonia in critically ill patients.

Atherosclerosis a common arterial disorder characterized by yellowish plaques of cholesterol, lipids, and cellular debris in the medial layer of the walls of the large and medium-sized arteries.

Atmospheric pressure pressure of the air on the earth at mean sea level; approximately 760 mm Hg (14.7 pounds per square inch).

Atria a chamber or cavity, such as the right and left atria of the heart or the nasal cavity.

Atrium (*pl. atria*) a chamber or cavity, such as the right and left atria of the heart or the nasal cavity.

Augment to enlarge or increase in size, amount, or degree; make bigger.

Automaticity the unique ability of the cells in the sinoatrial node of the heart to generate an action potential without being stimulated.

B

Bacteriuria the presence of bacteria in the urine.

Balloon angioplasty a method of dilating or opening an obstructed blood vessel by threading a small, balloon-tipped catheter into the vessel. The balloon is inflated to compress arteriosclerotic lesions against the walls of the vessel, leaving a larger lumen, through which blood can pass. It is used in treating arteriosclerotic heart disease.

Barometric pressure the pressure of the atmosphere usually expressed in terms of the height of a column of mercury.

Baroreceptor one of the pressure-sensitive nerve endings in the walls of the atria of the heart, the aortic arch, and the carotid sinuses. Baroreceptors stimulate central reflex mechanisms that allow physiologic adjustment and adaptation to changes in blood pressure via changes in heart rate, vasodilation, or vasoconstriction. Baroreceptors are essential for homeostasis. Also called *pressoreceptor*.

Basal pertaining to the fundamental or the basic, as basal anesthesia, which produces the first stage of unconsciousness, and the basal metabolic rate, which indicates the lowest metabolic rate; basal membrane.

Base a chemical compound that increases the concentration of hydroxide ions in aqueous solution.

Basophil a type of white blood cell that has a granular nucleus stained with basic dyes. These cells represent 1 percent or less of the total white blood cell count. Normal range: 0 to 0.75 percent of leukocyte differential.

Beta$_2$ (β_2) adrenergic drugs a class of drugs that act on the β_2 adrenergic receptor. Like other β adrenergic agonists, they cause smooth muscle relaxation. Also known as *adrenergic β_2 receptor agonists*.

Beta receptor any one of the postulated adrenergic (sympathetic fibers of autonomic nervous system) components of receptor tissues that respond to epinephrine and such blocking agents as propranolol. Activation of beta receptors causes various physiologic reactions such as relaxation of the bronchial muscles and an increase in the rate and force of cardiac contraction. Also called *beta-adrenergic receptor*. Compare **alpha receptor**.

Bicarbonate (HCO_3^-) an anion of carbonic acid in which only one of the hydrogen atoms has been removed, as in sodium bicarbonate ($NaHCO_3$).

Bicuspid valve the bicuspid valve is situated between the left atrium and the left ventricle and is the only valve with two rather than three cusps. The bicuspid valve allows blood to flow from the left atrium into the left ventricle but prevents blood from flowing back into the atrium. Ventricular contractions in systole forces the blood against the valve, closing the two cusps and assuring the flow of blood from the ventricle into the aorta. Also called the *mitral valve*.

Bifurcation a separation into two branches; the point of forking.

Biot's breathing short episodes of rapid, uniformly deep inspirations, followed by 10 to 30 seconds of apnea.

Blood the liquid pumped by the heart through all the arteries, veins, and capillaries. The blood is composed of a clear yellow fluid, called plasma, and the formed elements, and a series of cell types with different functions. The major function of the blood is to transport oxygen and nutrients to the cells and to remove carbon dioxide and other waste products from the cells for detoxification and elimination. Adults normally have a total blood volume of 7% to 8% of body weight, or 70 mL/kg of body weight for men and about 65 mL/kg for women. Blood is pumped through the body at a speed of about

30 cm/second, with a complete circulation time of 20 seconds.

Blood-brain barrier membrane between the circulating blood and the brain that prevents or slows the passage of some drugs and other chemical compounds, radioactive ions, and disease-causing organisms such as viruses from the blood into the central nervous system.

Blood doping the administration of blood, red blood cells, or related blood products to an athlete to enhance performance, often preceded by the withdrawal of blood so that training continues in a blood-depleted state.

Bohr effect as the PCO_2 level increases (increased H^+ concentration), the oxyhemoglobin saturation decreases, shifting the oxyhemoglobin dissociation curve to the right, whereas decreasing PCO_2 levels (decreased H^+ concentration) shift the curve to the left. The effect of PCO_2 and pH on the oxyhemoglobin curve is known as the Bohr effect.

Bolus intravenous bolus, a relatively large dose of medication administered into a vein in a short period, usually within 1 to 30 minutes.

Bradycardia a slow heartbeat marked by a pulse rate below 60 beats per minute in an adult.

Bradykinin a peptide produced by activation of the kinin system in a variety of inflammatory conditions. It is an extremely potent vasodilator; it also increases vascular permeability, stimulates pain receptors, and causes contraction of a variety of extravascular smooth muscles.

Bronchiectasis an abnormal condition of the bronchial tree characterized by irreversible dilation and destruction of the bronchial walls. The condition is sometimes congenital but is more often a result of bronchial infection or of obstruction by a tumor or an aspirated foreign body. Symptoms include a constant cough producing copious purulent sputum; hemoptysis; chronic sinusitis; clubbing of fingers; and persistent moist, coarse crackles. Some of the complications of bronchiectasis are pneumonia, lung abscess, empyema, brain abscess, and amyloidosis. Treatment includes frequent postural drainage, expectorants, antibiotics, and, rarely, surgical resection of the affected part of the lungs.

Bronchitis acute or chronic inflammation of the mucous membranes of the tracheobronchial tree. Caused by the spread of upper respiratory viral or sometimes bacterial infections to the bronchi, it is often observed with or after childhood infections, such as measles, whooping cough, diphtheria, and typhoid fever.

Bronchoconstriction a narrowing of the lumen of the bronchi restricting airflow to and from the lungs. See also **bronchospasm**.

Bronchodilator a substance, especially a drug, that relaxes contractions of the smooth muscle of the bronchioles to improve ventilation to the lungs. Pharmacologic bronchodilators are prescribed to improve aeration in asthma, bronchiectasis, bronchitis, and emphysema. Commonly used bronchodilators include albuterol, terbutaline, and various derivatives and combinations of these drugs. The adverse effects vary, depending on the particular class of bronchodilating drug. In general, bronchodilators are given with caution to people with impaired cardiac function. Nervousness, irritability, gastritis, or palpitations of the heart may occur.

Bronchospasm an excessive and prolonged contraction of the smooth muscle of the bronchi and bronchioles, resulting in an acute narrowing and obstruction of the respiratory airway. The contractions may be localized or general and may be cased by irritation or injury to the respiratory mucosa, infections, or allergies. A cough with generalized wheezing usually indicates the condition. Bronchospasm is a chief characteristic of asthma and bronchitis. Treatment includes the use of active bronchodilators, catecholamines, corticosteroids, or methylxanthines and preventive drugs such as cromolyn sodium. Also called **bronchoconstriction**.

Buffer a substance or group of substances that tends to control the hydrogen ion concentration in a solution by reacting with hydrogen ions of an acid added to the system and releasing hydrogen ions to a base added to the system. Buffers minimize significant changes of pH in a chemical system. Among the functions carried out by buffer systems in the body is maintenance of the acid–base balance of the blood and of the proper pH in kidney tubules.

Buffer action the property of a buffer solution to resist any change in its pH value even when small amount of the acid or the base is added to it.

C

Calcification process in which organic tissue becomes hardened by the deposition of lime salts in the tissue.

Calculus a pathologic stone formed of mineral salts. Calculi are usually found within hollow organs or ducts.

Caliber the inside diameter of a tube, commonly given in millimeters and fractions of an inch.

Canalicular pertaining to a small channel or canal.

Capacitance vessels the veins differ from the arteries in that they are capable of holding a large amount of blood with very little pressure change. Because of this unique feature, the veins are called capacitance vessels.

Capillary shunt a capillary shunt exists when blood flows from the right side of the heart to the left side without coming in contact with ventilated alveoli for gas exchange. Capillary shunting is commonly caused by (1) alveolar collapse or atelectasis, (2) alveolar fluid accumulation, or (3) alveolar consolidation.

Capillary stasis stagnation of normal flow of fluids or blood in capillaries.

Capnography the process of continuously recording the level of carbon dioxide in expired air. The percentage of carbon dioxide at the end of expiration can be estimated and gives a close approximation of the alveolar carbon dioxide concentration. The process, which requires the use of infrared spectroscopy, is used to monitor critically ill patients and in pulmonary function testing. The data are typically recorded automatically on a strip of graph paper on a bedside patient monitor

Carbon dioxide (CO_2) colorless, odorless, incombustible gas formed during respiration and combustion.

Carboxyhemoglobin a compound produced by the exposure of hemoglobin to carbon monoxide. Carbon monoxide from the environment is inhaled into the lungs, absorbed through the alveoli, and bound to hemoglobin in the blood, blocking the sites for oxygen transport. Oxygen levels decrease, and hypoxia and anoxia may result.

Cardiac output (CO) the total volume of blood discharged from the ventricles per minute.

Cardiac tamponade compression of the heart produced by the accumulation of blood or other fluid in the pericardial sac. Also called cardiac compression, pericardial tamponade.

Carotid sinus massage firm rubbing at the bifurcation of the carotid artery at the angle of the jaw. It creates an elevation of blood pressure in the carotid sinus that results in reflex slowing of atrioventricular conduction and sinus rate. The technique may be used to reduce the heart rate in tachyarrhythmia.

Cartilage dense, firm, compact connective tissue capable of withstanding considerable pressure and tension. Located in the tracheobronchial tree, all true joints, the outer ear, and the movable sections of the ribs.

Catecholamines biologically active amines that behave as epinephrine and norepinephrine.

Central venous pressure (CVP) pressure within the superior vena cava, which reflects the pressure under which the blood is returned to the right atrium.

Cerebrospinal fluid (CSF) fluid cushion that protects the brain and spinal cord from shock.

C-fibers an extensive network of free nerve endings located in the small conducting airways, blood vessels, and interstitial tissues between the pulmonary capillaries and alveolar walls. The C-fibers near the alveolar capillaries are called juxtapulmonary-capillary receptors, or J-receptors. These receptors react to certain chemicals and to mechanical stimulation. When stimulated, a reflex response triggers a rapid, shallow breathing pattern.

Chemoreceptor sense organ or sensory nerve ending, located outside the central nervous system, which is stimulated by and reacts to chemical stimuli.

Cheyne-Stokes respiration 10 to 30 seconds of apnea, followed by a gradual increase in the volume and frequency of breathing, followed by a gradual decrease in the volume of breathing until another period of apnea occurs.

Chloride shift during carbon dioxide transport, as HCO_3^- moves out of the red blood cells, the Cl^- (which has been liberated from the NaCl compound) moves into the red blood to maintain electric neutrality. This movement is known as the chloride shift or the *Hamburger phenomenon*.

Cholinergic receptor an integral membrane protein that responds to the binding of acetylcholine, a neurotransmitter; also called an *acetylcholine receptor* (abbreviated *AChR*).

Chordae tendineae the strands of tendon that anchor the cusps of the mitral and tricuspid valves to the papillary muscles of the ventricles of the heart, preventing prolapse of the valves into the atria during ventricular contraction.

Chronic persisting for a long period, often for the remainder of a person's lifetime. Compare **acute**.

Chronic alveolar hyperventilation with complete renal compensation a condition marked by low levels of carbon dioxide in the blood resulting from hyperventilation and a normal pH, which has been corrected by the excretion of HCO_3^- via the renal system. Also called chronic alveolar hyperventilation.

Chronic bronchitis a very common, debilitating pulmonary disease, characterized by greatly increased production of mucus by the glands of the trachea and bronchi and resulting in a cough with expectoration for at least 3 months of the year for more than 2 consecutive years.

Chronic obstructive pulmonary disease (COPD) a progressive and irreversible condition characterized by diminished inspiratory and expiratory capacity of the lungs. The condition is aggravated by cigarette smoking and air pollution. COPDs include asthma, chronic bronchiectasis, chronic bronchitis, and emphysema.

Chronic ventilatory failure with complete renal compensation a condition marked by high levels of carbon dioxide in the blood resulting from hypoventilation and a normal pH, which has been corrected by the retention of HCO_3^- via the renal system and/or the administration of HCO_3^-. Also called chronic ventilatory failure.

Cilia small, hairlike projections on the surface of specific epithelial cells. In the bronchi they propel mucus and foreign particles in a whiplike movement toward the throat.

Circulatory hypoxia a form of hypoxia in which the arterial blood reaching the tissue cells has a normal oxygen tension and content, but the amount of blood—and, therefore, the amount of oxygen—is not adequate to meet tissue needs.

Clinical manifestations symptoms or signs demonstrated by a patient.

Closed pneumothorax the presence of air or gas in the chest with the chest wall intact.

Colloid a state of matter composed of single large molecules or aggregations of smaller molecules of solids, liquids, or gases, in a continuous medium (dispersal medium), which also may be a solid, liquid, or gas.

Combined metabolic and respiratory alkalosis a blood pH above 7.45 caused by both a low carbon dioxide level and a high bicarbonate level. Also called metabolic and respiratory alkalosis.

Complete blood cell count a determination of the number of red and white blood cells per cubic millimeter of blood. A CBC is one of the most routinely performed tests in a clinical laboratory and one of the most valuable screening and diagnostic techniques. Most laboratories use an electronic counter for reporting numbers of red and white blood cells and platelets. Examining a stained slide of blood yields useful information about red cell morphologic characteristics and types of white blood cells (WBCs). The normal red blood cell (RBC) count in adult males is 4.7 to 6.1 million/mm^3. In adult females the normal RBC is 4.2 to 5.4 million/mm^3. Each type of white blood cell can be represented as a percentage of the total number of white cells observed. This is called a differential count. The normal adult WBC count is 5000 to 10,000/cm^3. Electronic blood counters also automatically determine hemoglobin or hematocrit and include this value in the CBC.

Composition makeup; what something is made of.

Compromise a blending of the qualities of two different things; an unfavorable change.

Concave a hollow surface, like the inside of a bowl.

Conception the union of sperm and ovum.

Conducting airways serve to conduct, clean, warm, and moisten the air to the alveoli via the nose, pharynx, larynx, trachea, bronchi, and bronchioles.

Conductivity the ability of the heart cells to transmit electrical current from cell to cell throughout the entire conductive system.

Congenital existing at and usually before birth; referring to conditions that are present at birth, regardless of their cause.

Congestion an abnormal accumulation of fluid in an organ or body area. The fluid is often mucus, but it may be bile or blood.

Congestive heart failure (CHF) an abnormal condition that reflects impaired cardiac pumping. Its causes include myocardial infarction, ischemic heart disease, and cardiomyopathy. Failure of the ventricles to eject blood efficiently results in volume overload, ventricular dilation, and elevated intracardiac pressure. Increased pressure in the left side of the heart causes pulmonary congestion; increased pressure in the right side causes systemic venous congestion and peripheral edema.

Consolidation the combining of separate parts into a single whole; a state of solidification; (in medicine) the process of becoming solid, as when lungs become firm and inelastic in pneumonia.

Constriction an abnormal closing or reduction in the size of an opening or passage of the body, as in vasoconstriction of a blood vessel.

Contiguous being in actual contact; touching along a boundary or at a point.

continuous positive airway pressure (CPAP) a method of noninvasive or invasive ventilation assisted by a flow of air delivered at a constant pressure throughout the respiratory cycle. It is performed for patients who can initiate their own respirations but who are not able to maintain adequate arterial oxygen levels without assistance. CPAP may be given through a ventilator and endotracheal tube, through a nasal cannula, or into a hood over the patient's head. Respiratory distress syndrome in the newborn and sleep apnea are often treated with CPAP. Also called constant positive airway pressure, continuous positive pressure breathing.

Contractility the ability of muscle tissue to contract when its thick (myosin) and thin (actin) filaments slide past each other.

Contusion injury in which the skin is not broken; a bruise.

Convex having a rounded, somewhat elevated surface, resembling a segment of the external surface of a sphere.

Cor pulmonale failure of the right ventricle resulting from disorders of the lungs or pulmonary vessels.

coronary angiography the x-ray visualization of the internal anatomy of the heart and blood vessels after the intravascular introduction of radiopaque contrast medium. The procedure is used as a diagnostic aid in myocardial infarction, vascular occlusion, calcified atherosclerotic plaques, cerebrovascular insult, portal hypertension, renal neoplasms, renal artery stenosis as a causative factor in hypertension, pulmonary emboli, and congenital and acquired lesions of pulmonary vessels. The contrast medium may be injected into an artery or vein or introduced into a catheter inserted in a peripheral artery and threaded through the vessel to a visceral site. Because the iodine in the contrast medium may cause a marked allergic reaction in some patients and may lead to death in severe cases, testing for hypersensitivity is indicated before the radiopaque substance is used. Because iodinated contrast agents are nephrotoxic, renal function also must be determined before angiography. After the procedure the patient is monitored for signs of bleeding at the puncture site, and bed rest for a number of hours is indicated.

coronary bypass open heart surgery in which a prosthesis or a section of a vein is grafted from the aorta onto one of the coronary arteries, bypassing a narrowing or blockage in the coronary artery. The operation is performed in coronary artery disease to improve the blood supply to the heart muscle and to relieve anginal pain. Coronary arteriography pinpoints the areas of obstruction before surgery. Under general anesthesia and with the use of a cardiopulmonary bypass machine, one end of a 15- to 20-cm prosthesis or a segment of saphenous vein from the patient's leg is grafted to the ascending aorta. The other end is sutured to the clogged coronary artery at a point distal to the stoppage. The internal mammary artery may also be used as graft tissue. Usually double or triple grafts are done for multiple areas of blockage. After surgery, close observation in an intensive care unit is essential to ensure adequate ventilation and cardiac output. The systolic blood pressure is not allowed to drop significantly below the preoperative baseline, nor is it allowed to rise significantly, because hypertension can rupture a graft site. Arrhythmias are treated with medications or by electrical cardioversion.

The patient is usually discharged within 5 to 8 days, unless complications occur.

Coronary sinus the wide venous channel, about 2.25 cm long, situated in the coronary sulcus and covered by muscular fibers from the left atrium. Through a single semilunar valve it drains five coronary veins: the great cardiac vein, the small cardiac vein, the middle cardiac vein, the posterior vein of the left ventricle, and the oblique vein of the left atrium.

Corpuscle any small, rounded body; an encapsulated sensory nerve ending.

Cortex the outer layer of an organ.

Cotyledons the visible segments on the maternal surface of the placenta. A typical placenta may have 15 to 28 cotyledons, each consisting of fetal vessels, chorionic villi, and intervillous space.

Crackle a common, abnormal respiratory sound consisting of discontinuous bubbling noises heard on auscultation of the chest during inspiration. Fine crackles have a popping sound produced by air entering distal bronchioles or alveoli that contain serous secretions, as in congestive heart failure, pneumonia, or early tuberculosis. Coarse crackles may originate in the larger bronchi have a lower pitch. Crackles are not cleared by coughing. Formerly called *rales*. Compare **rhonchus**, **wheeze**.

Creatinine a substance formed from the metabolism of creatine, commonly found in blood, urine, and muscle tissue.

Cribriform plate of the ethmoid bone plate received into the ethmoidal notch of the frontal bone and roofs in the nasal cavities.

Croup an acute viral infection of the upper and lower respiratory tract that occurs primarily in infants and young children 3 months to 3 years of age after an upper respiratory tract infection. It is characterized by hoarseness; irritability; fever; a distinctive harsh, brassy cough; persistent stridor during inspiration; and dyspnea and tachypnea, resulting from obstruction of the larynx. Cyanosis or pallor occurs in severe cases. The most common causative agents are the parainfluenza viruses, especially type 1, followed by the respiratory syncytial viruses and influenza A and B viruses. Also called *angina trachealis, exudative angina, laryngostasis*. Compare **acute epiglottitis**.

croup syndrome an abnormal high-pitched musical sound caused by an obstruction in the trachea or larynx. It is usually heard during inspiration. Stridor may indicate several neoplastic or inflammatory conditions, including glottic edema, asthma, diphtheria, laryngospasm, and papilloma.

Cystic fibrosis an inherited autosomal-recessive disorder of the exocrine glands, causing those glands to produce abnormally thick secretions of mucus, elevation of sweat electrolytes, increased organic and enzymatic constituents of saliva, and overactivity of the autonomic nervous system. The glands most affected are those in the pancreas and respiratory system and the sweat glands. Cystic fibrosis is usually recognized in infancy or early childhood, chiefly among Caucasians. The earliest manifestation is meconium ileus, an obstruction of the small bowel by viscid stool. Other early signs are a chronic cough; frequent, foul-smelling stools; and persistent upper respiratory infections. The most reliable diagnostic tool is the sweat test, which shows elevations of levels of both sodium and chloride. Because there is no known cure, treatment is directed at prevention of respiratory infections, which are the most frequent cause of death. Mucolytic agents and bronchodilators are used to help liquefy the thick, tenacious mucus. Physical therapy measures, such as postural drainage and breathing exercises, can also dislodge secretions. Broad-spectrum antibiotics may be used prophylactically.

D

Dead space ventilation volume of gas that is ventilated, but not physiologically effective. There are three types of dead space ventilation: *Anatomic dead space*—the volume of gas in the conducting airways: the nose, mouth, pharynx, larynx, and lower airways down to, but not including, the respiratory bronchioles. *Alveolar dead space*—alveoli that are ventilated, but not perfused with blood. *Physiologic dead space*—the sum of the anatomic dead space and alveolar dead space.

Deciliter (dL) one-tenth of a liter; 100 mL.

Defensin a peptide with natural antibiotic activity found within human neutrophils. Three types of defensins have been identified, each consisting of a chain of about 30 amino acids. Similar molecules occur in white blood cells of other animal species. They show activity toward viruses and fungi, in addition to bacteria.

Density mass of a substance per unit of volume (g/cm^3).

Deoxyhemoglobin hemoglobin not bound with oxygen. Also called *reduced hemoglobin*.

Deoxyribonucleic acid (DNA) a large, double-stranded, helical molecule that is the carrier of genetic information. In eukaryotic cells, it is found principally in the chromosomes of the nucleus. DNA is composed of four kinds of serially repeating nucleotide bases: adenine, cytosine, guanine, and thymine. Genetic information is coded in the sequence of the nucleotides. Also called *desoxyribonucleic acid*.

Depolarize to reduce to a nonpolarized condition; to reduce the amount of electrical charge between oppositely charged particles (ions).

Desquamation the process in which the cornified layer of the epidermis is sloughed in fine scales.

Determinant an element that identifies or determines the nature of something or that fixes or conditions an outcome.

Diabetes a general term referring to a variety of disorders characterized by excessive urination (polyuria), as in diabetes mellitus and diabetes insipidus.

Diagnostic pertaining to the use of scientific and skillful methods to establish the cause and nature of a sick person's disease.

Diapedesis the passage of red or white blood corpuscles through the walls of the vessels that contain them without damage to the vessels.

Diastole normal period in the heart cycle during which the muscle fibers lengthen, the heart dilates, and the chambers fill with blood.

Diastolic pressure the minimum level of blood pressure measured between contractions of the heart. It may vary with age, gender, body weight, emotional state, and other factors.

Differentiate to separate according to differences.

Diffusion the movement of gas molecules from an area of relatively high concentration of gas to one of low concentration. Different gases each move according to their own individual partial pressure gradients. Diffusion continues until all the gases in the two areas are in equilibrium.

Digitation a finger-like projection.

Distal away from or being the farthest from any point of reference.

Dorsal pertaining to the back or to the posterior portion of a body.

Driving pressure pressure difference between two areas in any vessel or airway.

Ductus arteriosus vessel between the left pulmonary artery and the aorta that bypasses the lungs in the fetus.

Dyspnea difficulty in breathing, of which the individual is aware.

E

Ectopic foci an area of the heart that produces abnormal beats. Ectopic foci may occur in both healthy and diseased hearts and are usually associated with irritation of a small area of myocardial tissue. They are produced in association with myocardial ischemia, drug (catecholamine) effects, emotional stress, and stimulation by foreign objects, including pacemaker catheters.

Edema a local or generalized condition in which the body tissues contain an excessive amount of extracellular fluid.

Efferent carrying away from a central organ or section.

Efferent nerves nerves that carry impulses from the brain or spinal cord to the periphery.

Elastance the natural ability of matter to respond directly to force and to return to its original resting position or shape after the external force no longer exists. In pulmonary physiology, elastance is defined as the change in pressure per change in volume.

Electrocardiogram (ECG) record of the electrical activity of the heart.

Electrolyte an element or compound that, when melted or dissolved in water or other solvent, dissociates into ions and is able to conduct an electric current.

Elongation the condition or process of being extended.

Embryonic pertaining to the early stages (i.e., first 3 months) of fetal development.

Emphysema an abnormal condition of the pulmonary system, characterized by overinflation and destructive changes in alveolar walls. It results in a loss of lung elasticity and decreased gas exchange. See also **pulmonary emphysema**.

Empyema an accumulation of pus in the pleural space, as a result of bacterial infection, such as pleurisy or tuberculosis. It is usually removed by surgical incision, aspiration, and drainage. Antibiotics, usually penicillin or vancomycin, are administered to combat the underlying infection. Oxygen therapy may also be administered.

End-expiration the portion of a ventilatory cycle at which expiration stops.

End-inspiration the portion of a ventilatory cycle at which inspiration stops.

Endocardium the lining of the heart chambers, containing small blood vessels and a few bundles of smooth muscle. It is continuous with the endothelium of the great blood vessels.

Endothelium the layer of epithelial cells, originating from the mesoderm, that lines the cavities of the heart, the blood and lymph vessels, and the serous cavities of the body.

Endotracheal within the trachea.

Endotracheal intubation the management of the patient with an airway catheter inserted through the mouth or nose into the trachea. An endotracheal tube may be used to maintain a patent airway, to prevent aspiration or material from the digestive tract in the unconscious or paralyzed patient, to permit suctioning of tracheobronchial secretions, or to administer positive-pressure ventilation that cannot be given effectively by a mask. Endotracheal tubes may be made of rubber or plastic and usually have an inflatable cuff to maintain a closed system with the ventilator.

Endotracheal tube a large-bore catheter inserted through the mouth or nose and into the trachea to a point above the bifurcation of the trachea. It is used for delivering oxygen under pressure when ventilation must be totally controlled and in general anesthetic procedures. See also **endotracheal intubation**.

Eosinophil a cell or cellular structure that stains readily with the acid stain eosin; specifically, a granular leukocyte. Normal range: 1 to 4 percent of leukocyte differential.

Epicardium one of the three layers of tissue that form the heart wall. It is composed of a single sheet of squamous epithelial cells overlying delicate connective tissue. Epicardium is the visceral portion (visceral layer) of the serous pericardium and folds back on itself to form the parietal portion of the serous pericardium.

Epinephrine one of two active hormones (the other is norepinephrine) secreted by the adrenal medulla.

Epistaxis bleeding from the nose. Also called *nosebleed*.

Equilibrium condition in which one or more forces are evenly balanced by opposite forces.

Erythrocyte a mature red blood cell (RBC).

Erythropoiesis the process of erythrocyte production involving the maturation of a nucleated precursor into a hemoglobin-filled nucleus-free erythrocyte that is regulated by erythropoietin, a hormone produced by the kidney.

Esophagus the esophagus (or oesophagus) is an organ in vertebrates which consists of a muscular tube through which food passes from the pharynx to the stomach. During swallowing, food passes from the mouth through the pharynx into the esophagus and travels via peristalsis to the stomach. The word esophagus is derived from the Latin œsophagus, which derives from the Greek word oisophagos, lit. "entrance for eating." In humans the esophagus is continuous with the laryngeal part of the pharynx at the level of the C6 vertebra. The esophagus passes through posterior mediastinum in thorax and enters abdomen through a hole in the diaphragm at the level of the tenth thoracic vertebrae (T10). It is usually about 25–30 cm long depending on individual height. It is divided into cervical, thoracic and abdominal parts. Due to the inferior pharyngeal constrictor muscle, the entry to the esophagus opens only when swallowing or vomiting.

Ethmoid bone the very light, sievelike, and spongy bone at the base of the cranium, also forming the roof and most of the walls of the superior part of the nasal cavity. It consists of four parts: a horizontal plate, a perpendicular plate, and two lateral labyrinths.

Etiology study of the cause of disease.

Eupnea normal, spontaneous breathing.

Excitability the ability of a cell to reach its threshold potential and respond to a stimulus or irritation. The lower the stimulus needed to activate a cell, the more excitable the cell; conversely, the greater the stimulus needed, the less excitable the cell.

Excretion elimination of waste products from the body.

Excursion the extent of movement from a central position or axis.

Expectoration clearing the lungs by coughing up and spitting out matter.

Expiratory reserve volume (ERV) the maximum volume of air that can be exhaled after a normal tidal volume exhalation.

External respiration gas exchange between the pulmonary capillaries and the alveoli.

Extra-alveolar pertaining to the area outside of the alveoli.

Extracellular outside a cell or in the cavities or spaces between cell layers or groups of cells.

Extravascular outside a vessel.

F

Fascia the fibrous connective membrane of the body that may be separated from other specifically organized structures, such as the tendons, the aponeuroses, and the ligaments, and that covers, supports, and separates muscles.

Fertilization the union of sperm and ovum.

Fetus the developing human *in utero* from the third month to birth.

FEV_1 forced expiratory volume in one second.

Fibrin whitish, filamentous protein formed by the action of thrombin on fibrinogen.

Fibroelastic composed of fibrous and elastic tissue.

Fibrosis the repair and replacement of inflamed tissues or organs by connective tissues. The process results in the replacement of normal cells by fibroblasts (and eventually, the replacement of normal organ tissue by scar tissue).

Fissure cleft or groove on the surface of an organ, often marking the division of the organ into parts, such as the lobes of the lung.

Fistula abnormal passage or communication, usually between two internal organs or leading from an internal organ to the surface of the body.

Fixed acid an acid produced in the body from sources other than carbon dioxide and not excreted by the lungs. They are produced from an incomplete metabolism of carbohydrates, fats, and proteins; also known as a *nonvolatile* or *metabolic acid*.

Flail chest a thorax in which multiple rib fractures cause instability in part of the chest wall and paradoxical breathing, with the lung underlying the injured areas moving in on inspiration and bulging on expiration. If it is uncorrected, hypoxia will result.

Flex to contract, as a muscle; to increase the angle of a joint.

Foramen ovale an opening in the septum between the right and the left atria in the fetal heart. This opening provides a bypass for blood that would otherwise flow to the fetal lungs. After birth the foramen ovale functionally closes when the newborn takes the first breath and full circulation through the lungs begins.

Forced vital capacity the maximum volume of gas that can be forcibly and rapidly exhaled after a full inspiration.

Frank-Starling curve a graphic illustration that shows the relationship between the degree of myocardial stretch and cardiac output.

Friction rub a dry, grating sound heard with a stethoscope during auscultation. It is a normal finding when heard over the liver and splenic areas. A friction rub auscultated over the pericardial area is suggestive of pericarditis; a rub over the pleural area may be a sign of lung disease.

Frontal process of the maxilla (nasal process) a strong plate that projects upward, medially ward, and backward by the side of the nose, forming part of its lateral boundary.

Functional residual capacity (FRC) the volume of air remaining in the lungs after a normal exhalation.

Functionally according to its proper use or action; working as it should.

FVC the maximum volume of gas that can be forcibly and rapidly exhaled after a full inspiration.

G

Gastrointestinal tract the route taken by food from the stomach to the rectum.

Generation the process of forming a new organism or part of an organism in the airways; a sequential, numbered branch off the trachea.

Gestation the period of time from the fertilization of the ovum until birth.

Glomerulonephritis inflammation of the glomerulus in the nephron of the kidney.

Glomerulus a tuft or cluster; a structure composed of blood vessels or nerve fibers, such as a *renal glomerulus*.

Glossopharyngeal nerve the ninth cranial nerve.

Glottis the glottis is defined as the combination of the vocal folds (vocal cords) and the space in between the folds (the rima glottidis).

Glycoprotein any of a class of conjugated proteins consisting of a compound of a protein with a carbohydrate group.

Goblet cell one of many specialized epithelial cells that secrete mucus and form glands of the epithelium of the stomach, the intestine, and parts of the respiratory tract.

Gradient a slope or grade; a difference in values between two points.

Gram percent (g%) the number of grams of a substance in 100 mL of fluid.

Granulocyte a type of leukocyte characterized by the presence of cytoplasmic granules.

Gravity the universal effect of the attraction between any body of matter and any planetary body. The force of the attraction depends on the relative masses of the bodies and on the inverse of the square of the distance between them.

Gravity dependent a phrase used to describe the natural tendency of blood, which is a relatively heavy substance, to move to the portion of the body, or portion of the organ, that is closest to the ground.

Greater alar cartilage (lower lateral cartilage) a thin, flexible plate, situated immediately below the lateral nasal cartilage and bent upon itself in such a manner as to form the medial wall and lateral wall of the nostril of its own side.

H

Haemophilus influenzae type B (HIB) a bacterium capable of causing a range of diseases, including ear infections, cellulitis (soft tissue infection), upper respiratory infections, pneumonia, and such serious invasive infections as meningitis with potential brain damage and epiglottitis with airway obstruction. It spreads by droplet through coughs and sneezing.

Haldane effect the phenomenon in which deoxygenated blood enhances the loading of carbon dioxide and the oxygenation of blood enhances the unloading of carbon dioxide during carbon dioxide transport.

Hamburger phenomenon see **chloride shift**.

Heart the muscular cone-shaped hollow organ, about the size of a clenched fist, that pumps blood throughout the body and beats normally about 70 times per minute by coordinated nerve impulses and muscular contractions. Enclosed in pericardium, it rests on the diaphragm between the lower borders of the lungs, occupying the middle of the mediastinum. It is covered ventrally by the sternum and the adjoining parts of the third to the sixth costal cartilages. The organ is about 12 cm long, 8 cm wide at its broadest part, and 6 cm thick. The weight of the heart in men averages between 280 and 340 g and in women, between 230 and 280 g. The layers of the heart, starting from the outside, are the epicardium, the myocardium, and the endocardium. The chambers include two ventricles with thick muscular walls, making up the bulk of the organ, and two atria with thin muscular walls. A septum separates the ventricles and extends between the atria (interatrial septum), dividing the heart into the right and the left sides. The left side of the heart pumps oxygenated blood into the aorta and on to all parts of the body. The right side receives deoxygenated blood from the vena cava and pumps it into the pulmonary arteries. The valves of the heart include the tricuspid valve, the bicuspid (mitral) valve, the semilunar aortic valve, and the semilunar pulmonary valve. The sinoatrial node in the right atrium of the heart (under the control of the medulla oblongata in the brainstem) initiates the cardiac impulse, causing the atria to contract. The atrioventricular (AV) node near the septal wall of the right atrium spreads the impulse over the AV bundle (bundle of His) and its branches, causing the ventricles to contract. Both atria contract simultaneously, followed quickly by the simultaneous contraction of the ventricles. The sinoatrial node of the heartbeat sets the rate. Other factors affecting the heartbeat are emotion, exercise, hormones, temperature, pain, and stress.

Hematocrit volume of erythrocytes packed by centrifugation in a given volume of blood; is expressed as the percentage of total blood volume that consists of erythrocytes.

Hemodynamics the study of the physical aspects of blood circulation, including cardiac function and peripheral vascular physiologic characteristics.

Hemoglobin a complex protein-iron compound in the blood that carries oxygen to the cells from the lungs and carbon dioxide away from the cells to the lungs. Each erythrocyte contains 200 to 300 molecules of hemoglobin.

Hemolysis the breakdown of red blood cells and the release of hemoglobin.

Heparin a polysaccharide produced by the mast cells of the liver and by basophil leukocytes that inhibits coagulation by preventing conversion of prothrombin to thrombin. It also inhibits coagulation by preventing liberation of thromboplastin from blood platelets.

Histamine a substance that is normally present in the body and exerts a pharmacologic action when released from injured cells. It is produced from the amino acid *histidine*.

Histotoxic hypoxia a type of hypoxia that develops in any condition that impairs the ability of tissue cells to utilize oxygen.

Homeostasis a physiologic state resulting from a dynamic equilibrium maintained by monitoring processes and altered effector activity, incorporating negative feedback pathways.

Hormone a substance originating in an organ or gland that is conveyed through the body to another part of the body, which it stimulates by chemical action to increased functional activity and/or increased secretion.

Hydrogen ion strictly, the nucleus of a hydrogen atom separated from its accompanying electron. The hydrogen nucleus is made up of a particle carrying a unit positive electric charge, called a proton. The isolated hydrogen ion, represented by the symbol H^+, is therefore customarily used to represent a proton.

Hydrostatic pertaining to the pressure of liquids in equilibrium and the pressure exerted on liquids.

Hydrous containing water, usually chemically combined.

Hydroxide ions molecular ions with the formula OH^-, formed by the loss of a proton from a water molecule. When dissolved in water, the hydroxide ion is the strongest base that can exist in aqueous solution.

Hyperbaric oxygen therapy (HBOT) the administration of oxygen at greater than normal atmospheric pressure. The procedure is performed in specially designed chambers that permit the delivery of 100% oxygen at atmospheric pressure that is three times normal. The technique is used to overcome the natural limit of oxygen solubility in blood, which is about 0.3 mL of oxygen per 100 mL of blood. In hyperbaric oxygenation, dissolved oxygen can be increased to almost 6 mL per 100 mL and the P_{O_2} in blood may be nearly 2000 mm Hg at 3 atmospheres absolute. Hyperbaric oxygenation has been used to treat carbon monoxide poisoning, air embolism, smoke inhalation, acute cyanide poisoning, decompression sickness, wounds, clostridial myonecrosis, and certain cases of blood loss or anemia in which increased oxygen transport may compensate in part for hemoglobin deficiency. Factors limiting the usefulness of hyperbaric oxygenation include the hazards of fire and explosive decompression, pulmonary damage and neurologic toxicity at high atmospheric pressures, cardiovascular debility of the patient, and the need to interrupt treatments repeatedly because exposures at maximum atmospheric pressures must be limited to 90 minutes. Also called hyperbaric oxygen.

Hypercapnia greater than normal amount of carbon dioxide in the blood. Also called *hypercarbia*.

Hyperchloremia an excessive level of chloride in the blood that results in acidosis.

Hyperinflation distention by air, gas, or liquid, as in the hyperinflation of the alveoli.

Hyperkalemia increased amount of potassium in the blood.

Hyperpnea increased depth (volume) of breathing, with or without an increased frequency.

Hypersecretion substance or fluid produced by cells or glands in an excessive amount or more than normal.

Hypersensitivity an abnormal condition characterized by an exaggerated response of the immune system to an antigen.

Hypertension higher than normal blood pressure.

Hyperthermia higher than normal body temperature.

Hyperventilation pulmonary ventilation rate greater than that metabolically necessary for gas exchange, resulting from an increased respiration rate, an increased tidal volume, or both. Hyperventilation causes an excessive intake of oxygen and elimination of carbon dioxide and may cause hyperoxygenenation. Hypocapnia and respiratory alkalosis then occur, leading to dizziness, faintness, numbness of the fingers and toes, possibly syncope, and psychomotor impairment. Causes of hyperventilation include asthma or early emphysema; increased metabolic rate caused by exercise, fever, hyperthyroidism, or infection; lesions of the central nervous system, as in cerebral thrombosis, encephalitis, head injuries, or meningitis; hypoxia or metabolic acidosis; use of hormones and drugs, such as epINEPHrine, progesterone, and salicylates; difficulties with mechanical respirators; and psychogenic factors, such as acute anxiety or pain. Compare hypoventilation.

Hypochloremia a decreased amount of chloride in the blood.

Hypokalemia a decreased amount of potassium in the blood.

Hypoperfusion deficiency of blood coursing through the vessels of the circulatory system.

Hypothalamus portion of the brain that controls certain metabolic activities.

Hypoventilation an abnormal condition of the respiratory system that occurs when the volume of air that enters the alveoli and takes part in gas exchange is not adequate for the body's metabolic needs. It is characterized by cyanosis, polycythemia, increased Pa_{CO_2}, and generalized decreased respiratory function. Hypoventilation may be caused by an uneven distribution of inspired air (as in bronchitis), obesity, neuromuscular or skeletal disease affecting the thorax, decreased response of the respiratory center to carbon dioxide, or a reduced amount of functional lung tissue, as in atelectasis, emphysema, and pleural effusion. The results of hypoventilation are hypoxia, hypercapnia, pulmonary hypertension with cor pulmonale, and respiratory acidosis. Treatment includes weight reduction in cases of obesity, artificial respiration, and possibly tracheostomy.

Hypoxemia an abnormal deficiency in the concentration of oxygen in arterial blood. Symptoms of acute hypoxemia are cyanosis, restlessness, stupor, coma, Cheyne-Stokes respiration, apnea, increased blood pressure, tachycardia, and an initial increase in cardiac output that later falls, producing hypotension and ventricular fibrillation or asystole.

Hypoxia inadequate oxygen tension at the cellular level, characterized by tachycardia, hypertension, peripheral vasoconstriction, dizziness, and mental confusion.

I

Iatrogenic pneumothorax a condition in which air or gas is present in the pleural cavity as a result of mechanical ventilation, tracheostomy tube placement, or other therapeutic intervention.

Iliac crest long curved upper margin of the hip bone.

Immaturity the state of being not fully developed or ripened.

Immunoglobulin one of a family of closely related but not identical proteins that are capable of acting as antibodies.

Immunologic mechanism reaction of the body to substances that are foreign or are interpreted by the body as foreign.

Impede to slow down; to stand in the way of; to fight against.

Inferior vena cava (IVC) venous trunk for the lower extremities and the pelvic and abdominal viscera.

Inflammation the protective response of body tissues to irritation or injury. Inflammation may be acute or chronic; its cardinal signs are redness, heat, swelling, and pain, often accompanied by loss of function. The process begins with a transitory vasoconstriction, then is followed by a brief increase in vascular permeability. The second stage is prolonged and consists of sustained increase in vascular permeability, exudation of fluids from the vessels, clustering of leukocytes along the vessels walls, phagocytosis of microorganisms, deposition of fibrin in the vessel, disposal of the accumulated debris by macrophages, and finally migration of fibroblast to the area and development of new, normal cells. The severity, timing, and local character of any particular inflammatory response depend on the cause, the area affected, and the condition of the host. Histamine, kinins, and various other substances mediate the inflammatory process.

Inguinal ligament a fibrous band formed by the inferior border of the aponeurosis of the external oblique that extends from the anterior superior iliac spine to the pubic tubercle.

Inhibitory repressive; tending to restrain a function.

Innervation the distribution or supply of nerve fibers or nerve impulses to a body part.

Inotrope the most commonly used term used for various drugs that affect the strength of contraction of the heart muscle (myocardial contractility). A drug may be classified as either a negative or positive inotropic agent. *Negatively* inotropic agents weaken the force of muscular contractions. *Positively* inotropic agents increase the strength of muscular contraction.

Insomnia chronic inability to sleep or to remain asleep throughout the night; wakefulness; sleeplessness. Insomnia may be the symptom of a psychiatric disorder.

Inspiratory capacity the volume of air that can be inhaled after a normal exhalation.

Inspiratory reserve volume (IRV) the maximum volume of air that can be inhaled after a normal tidal volume inhalation.

Inspiratory stridor stridor is a high pitched wheezing sound resulting from turbulent air flow in the upper airway. Stridor is a physical sign which is produced by narrow or obstructed airway path. It can be inspiratory, expiratory or biphasic. Inspiratory stridor is common.

Interatrial septum the partition or wall that separates the right and left atrium of the heart.

Internal respiration gas exchange between the systemic capillaries and the cells.

Interstitial placed or lying between; pertaining to the interstices or spaces within an organ or tissue.

Interventricular septum the partition or wall that separates the right and left ventricles of the heart.

Intra prefix meaning within.

Intra-alveolar within the alveoli.

Intrapleural within the pleura.

Intrapulmonary within the lungs.

Intrarenal within the kidneys.

Intratubular within a tube.

Intrinsic an intrinsic property is an essential or inherent property of a system or of a material itself or within. It is independent of how much of the material is present and is independent of the form the material, e.g., one large piece or a collection of smaller pieces. Intrinsic properties are dependent mainly on the chemical composition or structure of the material.

Intubation passage of a tube into a body aperture; specifically, the insertion of a breathing tube through the mouth or nose or into the trachea to ensure a patent airway for the delivery of anesthetic gases and oxygen or both. Kinds of intubation include **endotracheal intubation** and *nasotracheal intubation*.

Inverse opposite in order, nature, or effect; as one variable increases, the other decreases.

Ion atom, group of atoms, or molecule that has acquired a net electrical charge by gaining or losing electrons.

Ischemia decreased blood supply to a body organ or part.

Isobar a line on a map, chart, or nomogram connecting areas of equal pressure.

K

Ketoacidosis acidosis accompanied by an accumulation of ketones in the body, resulting from extensive breakdown of fats because of faulty carbohydrate metabolism. It occurs primarily as a complication of diabetes mellitus and is characterized by a fruity odor of acetone on the breath, mental confusion, dyspnea, nausea, vomiting, dehydration, weight loss, and, if untreated, coma.

Kussmaul breathing abnormally deep, very rapid sighing respirations characteristic of diabetic ketoacidosis.

L

Lactic acid acid formed in muscles during activity by the breakdown of sugar without oxygen.

Laryngitis an inflammation of the larynx. It causes hoarse voice or the complete loss of the voice because of irritation to the vocal folds (vocal cords). Dysphonia is the medical term for a vocal disorder, of which laryngitis is one cause. Laryngitis is categorized as acute if it lasts less than a few days. Otherwise it is categorized as chronic, and may last over 3 weeks. The chronic form of disease occurs mostly in middle age and is much more common in men than women.

Laryngopharynx the laryngopharynx or hypopharynx (Latin: pars laryngea pharyngis) is the caudal part of the pharynx; it is the part of the throat that connects to the esophagus. It lies inferior to the epiglottis and extends to the location where this common pathway diverges into the respiratory (larynx) and digestive (esophagus) pathways. At that point, the laryngopharynx is continuous with the esophagus posteriorly. The esophagus conducts food and fluids to the stomach; air enters the larynx anteriorly. During swallowing, food has the "right of way", and air passage temporarily stops. Corresponding roughly to the area located between the 4th and 6th cervical vertebrae, the superior boundary of the laryngopharynx is at the level of the hyoid bone. The laryngopharynx includes three major sites: the pyriform sinus, postcricoid area, and the posterior pharyngeal wall. Like the oropharynx above it, the laryngopharynx serves as a passageway for food and air and is lined with a stratified squamous epithelium. It is innervated by the pharyngeal plexus.

Laryngotracheobronchitis laryngotracheobronchitis (or croup) is a respiratory condition that is usually triggered by an acute viral infection of the upper airway. The infection leads to swelling inside the throat, which interferes with normal breathing and produces the classical symptoms of a "barking" cough, stridor, and hoarseness. It may produce mild, moderate, or severe symptoms, which often worsen at night. It is often treated with a single dose of oral steroids; occasionally epinephrine is used in more severe cases. Hospitalization is rarely required.

Larynx the organ of voice that is part of the upper airway passage connecting the pharynx with the trachea. It accounts for a large bump in the neck called the Adam's apple and is larger in men than in omen, although it remains the same size in men and women until puberty. The larynx forms the caudal portion of the anterior wall of the pharynx and is lined with mucous membrane that is continous with that of the pahrynx and the trachea. The larynx exends vertically to the fourth, fifth, and sixth cervical vertebrae and is somewhat higher in the female and during childhood. It is composed of three single cartilages and three paired cartilages, all connected together by ligaments and moved by various muscles. The single cartilages are the thyroid, cricoid, and epiglottis. The paired cartilages are the arytenoid, corniculate, and cuneiform, which support the vocal folds.

Lesser alar cartilages the part of the nose that forms the lateral wall and is curved to correspond with the ala of the nose; it is oval and flattened, narrow behind, where it is connected with the frontal process of the maxilla by a tough fibrous membrane, in which are found three or four small nasal cartilages; also referred to as *minor alar* or *accessory quadrate*.

Leukocyte a white blood cell, one of the formed elements of the circulating blood system. Five types of leukocytes are classified by the presence or absence of granules in the cytoplasm of the cell. Normal range: 5000 to 10,000/mm^3. The agranulocytes are lymphocytes and monocytes. The granulocytes are neutrophils, basophils, and eosinophils. Also called *leucocyte*, *white blood cell*, and *white corpuscle*.

Leukocytosis an abnormal increase in the number of circulating white blood cells. An increase often accompanies bacterial, but not usually viral, infections. The normal range is 5000 to 10,000/mm^3. Leukemia may be associated with a white blood cell count as high as 500,000 to 1 million per cubic millimeter of blood, the increase being either equally or disproportionately distributed among all types. Kinds of leukocytosis include *basophilia, eosinophilia*, and *neutrophilia*.

Ligamentum nuchae upward continuation of the supraspinous ligament, extending from the seventh cervical vertebra to the occipital bone.

Lingual frenulum a small fold of mucous membrane extending from the floor of the mouth to the midline of the underside of the tongue.

Lingual tonsil a mass of lymphoid follicles near the root of the tongue. Each follicle forms a rounded eminence containing a small opening leading into a funnel-shaped cavity surrounded by lymphoid tissue.

Linea alba "white line" of connective tissue in the middle of the abdomen from sternum to pubis.

Linear response a response or output that is directly proportional to the input.

Lipid any of numerous fats generally insoluble in water that constitute one of the principal structural materials of cells.

Lobar pertaining to a lobe, such as the lobes of the lung.

Lower airways the lower airways consist of the following tracheobronchial tree components below the larynx: trachea, main stem bronchi, lobar bronchi, semental bronchi, and subsegmental bronchi.

Lumen inner open space of a tubular organ, such as a blood vessel or intestine.

Lung capacities two or more lung volumes.

Lung compliance a measure of the ease of expansion of the lungs and thorax. It is determined by pulmonary volume and elasticity. A high degree of compliance indicates a loss of elastic recoil of the lungs, as in old age or emphysema. Decreased compliance means a greater change in pressure is needed for a given change in volume, as in atelectasis, edema, fibrosis, pneumonia, or absence of surfactant. Dyspnea on exertion is the main symptom of diminished lung compliance.

Lymphocyte small agranulocytic leukocytes originating from fetal stem cells and developing in the bone marrow. Lymphocytes normally comprise 25 percent of the total white blood cell count but increase in number in response to infection. Two forms occur: B cells and T cells. B cells circulate in an immature form and synthesize antibodies for insertion into their own cytoplasmic membranes. T cells are lymphocytes that have circulated through the thymus gland and have differentiated to become thymocytes. When exposed to an antigen, they divide rapidly and produce large numbers of new T cells sensitized to that antigen.

M

Macrophage any phagocytic cell of the reticuloendothelial system, including specialized Kupffer's cells in the liver, lungs, spleen, and histocyte in loose connective tissue.

Magnitude pertaining to size.

Malar pertaining to the cheek or cheekbones.

Malformation deformity; abnormal shape or structure, especially congenital.

Manubriosternal joint the early union, by hyaline cartilage, of the manubrium and the body of the sternum, which later becomes a symphysial type of joint. Also called the sternal angle or angle of Louis.

Mastoid process projection of the posterior portion of the temporal bone; gives attachment to the sternocleidomastoid, splenius capitis, and longissimus capitis muscles.

Maxilla one of a pair of large bones (often referred to as one bone) that form the upper jaw and teeth, consisting of a pyramidal body and four processes: the zygomatic, frontal, alveolar, and palatine.

Maxillary pertaining to the upper jawbone.

Mean occupying a middle position; being near the average.

Mechanical relating to physical properties.

Mechanoreceptor receptor that receives mechanical stimuli such as pressure from sound or touch.

Medial pertaining to the middle.

Mediastinum a part of the thoracic cavity in the middle of the thorax, between the pleural sacs containing the two lungs. It extends from the sternum to the vertebral column and contains all the thoracic viscera except the lungs. It is enclosed in a thick extension of the thoracic subserous fascia and is divided into the cranial part and the caudal part.

Mediated between two parts or sides.

Medulla oblongata a bulbous continuation of the spinal cord just above the foramen magnum and separated from the pons by a horizontal groove. It is one of three parts of the brainstem and mainly contains white substance with some mixture of gray substance. The medulla contains the cardiac, vasomotor, and respiratory centers of the brain; medullary injury or disease often proves fatal.

Mesoderm the middle of the three cell layers of the developing embryo, which lies between the ectoderm and endoderm.

Metabolic acid an acid produced in the body from sources other than carbon dioxide and not excreted by the lungs. They are produced from an incomplete metabolism of carbohydrates, fats, and proteins; also known as a *nonvolatile acid* or *fixed acid*.

Metabolic acidosis acidosis in which excess acid is added to the body fluids or bicarbonate is lost from them. Metabolis acidosis is indicated by a blood pH below 7.35 and a normal carbon dioxide level (35 to 45 torr).

metabolic alkalosis alkalosis in which excess bicarbonate is added to the body fluids or acid is lost from them. Metabolic alkalosis is indicated by a blood pH above 7.45 and a normal carbon dioxide level (35 to 45 torr).

metabolic and respiratory acidosis a blood pH below 7.35 caused by both a high carbon dioxide level and a low bicarbonate level. Also called combined metabolic and respiraory acidosis.

Metabolism sum of all physical and chemical changes that take place within an organism; all energy and material transformations that occur within living cells.

Microvilli minute cylindrical processes on the free surface of a cell (especially cells of the proximal convoluted renal tubule and those of the intestinal epithelium), which increase the surface area of the cell.

Mild hypoxemia an arterial oxgen pressure (Pa_{O_2}) between 60 and 80 mm Hg.

Mitral valve see **bicuspid valve**.

Moderate hypoxemia an arterial oxgen pressure (Pa_{O_2}) between 40 and 60 mm Hg.

Molecular weight weight of a molecule attained by adding the atomic weight of its constituent atoms.

Monocyte a large, mononuclear leukocyte normally found in lymph nodes, spleen, bone marrow, and loose connective tissue. Normal range: 3 to 7 percent of leukocyte differential.

Motor nerve a nerve consisting of efferent fibers that conduct impulses from the brain or the spinal cord to one of the muscles or organs.

Mucous pertaining to or resembling mucus; secreting mucus.

Mucus the viscous, slippery secretions of mucous membranes and glands, containing mucin, white blood cells, water, inorganic salts, and exfoliated cells.

Myelin a lipoproteinaceous substance constituting the sheaths of various nerve fibers throughout the body and enveloping the axis of myelinated nerves. It is largely composed of phospholipids and protein, which gives the fibers a white, creamy color. It is largely composed of fat, giving the fibers a white, creamy color.

Myocardial infarction necrosis of a portion of cardiac muscle caused by an obstruction in a coronary artery resulting from atherosclerosis, a thrombus, or a spasm. Also called heart attack.

Myocardium a thick contractile middle layer of uniquely constructed and arranged muscle cells that forms the bulk of the heart wall. The myocardium contains a minimum of other tissue, except blood vessels, and is covered interiorly by the endocardium. The contractile tissue of the myocardium is composed of fibers with the characteristic cross-striations of muscular tissue. The fibers are about one third as large in diameter as those of skeletal muscle and contain more sarcoplasm. They branch frequently and are interconnected to form a network that is continuous except where the bundles and the laminae are attached at their origins and insertions into the fibrous trigone of the heart. Myocardial muscle contains less connective tissue than does skeletal muscle. Specially modified fibers of myocardial muscle constitute the conduction system of the heart, including the sinoatrial node, the atrioventricular (AV) node, the AV bundle, and the Purkinje fibers. Most of the myocardial fibers function to contract the heart. The metabolic processes of the myocardium are almost exclusively aerobic. Many key enzymatic reactions of the heart, such as the citric acid cycle and oxidative phosphorylation, take place in the highly concentrated myocardial sarcosomes. The process of oxidative phosphorylation produces adenosine triphosphate (ATP), the immediate energy source for myocardial contraction. Oxygen, which significantly affects ATP production and contractibility, is a critical metabolic component of the myocardium, which consumes from 6.5 to 10 mL/100 g of tissue per minute. Without this oxygen supply, myocardial contractions decrease in a few minutes. The myocardium maintains a relatively constant level of glycogen in the form of sarcoplasmic granule.

Myoepithelial cells spindle-shaped cells found around sweat, mammary, and salivary glands. The myoepithelial cells are contractile and resemble smooth muscle cells.

Myoglobin a ferrous globin complex consisting of one heme group and one globin polypeptide chain. It is responsible for the red pigment seen in skeletal muscle.

N

Narcolepsy a sleep disorder that is characterized by excessive sleepiness, sleep attacks, sleep paralysis, hallucinations and, for some, sudden loss of muscle control (cataplexy).

Nares the pairs of anterior and posterior openings to the nasal cavity that allow the passage of air to the pharynx and ultimately the lungs during respiration.

Nasal bones two small oblong bones, varying in size and form in different individuals; they are placed side-by-side at the middle and upper part of the face and form, by their junction, "the bridge" of the nose. Each has two surfaces and four borders.

Nasal septum the partition dividing the nostrils. It is composed of bone and cartilage covered by mucous membrane.

Necrosis localized tissue death that occurs in groups of cells in response to disease or injury.

Neoplasm any abnormal growth of new tissue, benign or malignant. Also called *tumor*.

Neuropathy any abnormal condition characterized by inflammation and degeneration of the peripheral nerves.

Neutrophil a polymorphonuclear, granular leukocyte that stains easily with neutral dyes. The nucleus stains dark blue and contains three to five lobes connected by slender threads of chromatin. The cytoplasm contains fine, inconspicuous granules. Neutrophils are the circulating white blood cells essential for phagocytosis and proteolysis by which bacteria, cellular debris, and solid particles are removed and destroyed. Normal range: 57 to 67 percent of leukocyte differential.

Nomogram a graph consisting of several lines or curves (usually parallel) graduated for different variables in such a way that a straight line cutting the three lines gives the related values of the three variables.

Nonlinear having or being a response or output that is not directly proportional to the input.

Nonvolatile acid an acid produced in the body from sources other than carbon dioxide and not excreted by the lungs. They are produced from an incomplete metabolism of carbohydrates, fats, and proteins; also known as a *fixed acid* or *metabolic acid*.

Norepinephrine one of two active hormones (the other is epinephrine) secreted by the adrenal medulla. It is chiefly a vasoconstrictor and has little effect on cardiac output.

Nose the structure that protrudes from the anterior part of the face and seves as a passagway for air to and from the lungs. The nose filers the air, warming, moistening, and chemcally examining it for impurities that might irritate the mucous lining of the respiratory tract. The nose also contains receptor cells for smell, and it aids the faculty of speech. It consists of an internal and an external part. The external part, which protudes from the face, is considerably smaller than the internal part, whcih lies over the roof of the mouth. The hollow interior part is separated into a right and a left cavity by a septum. Each cavity is divided into the superior, middle and inferior meati by the projection of nasal conchae. The external part of the nose is perforated by two nostrils (anterior nares), and the internal part by two posterior nares. The pairs of sinuses that drain into the nose are the frontal, maxillary, ethmoidal, and sphenoidal sinuses. Ciliated mucous membrane lines the nose, closely abhering to the periosteum. The mucous membrane is continous withthe skin through the nares and with the mucous membrane of the nasal part of the pharynx through the choanae. The mucous membrane contains the olfactory cells that form the olfactory nerve that enters the cranium.

Nostrils the ends of the nostrils that open anteriorly into the nasal cavity and allow the inhalation and the exhalation of air. Each is an oval opening that measures about 1.5 cm anteroposteriorly and about 1 cm in diameter. The anterior nares connect with the nasal fossae. Also called anterior nares.

O

Obstructive lung disorder obstructive respiratory disease is the result of a reduction of airway size that impedes air flow. The obstruction may result from bronchospasm, edema of the bronchial mucosa, or excessive bronchial secretions. Obstructive disease is characterized by reduced expiratory flow rates and increased total lung capacity. Acute obstructive respiratory diseases include asthma, bronchitis, and bronchiectasis; chronic obstructive diseases include emphysema, chronic bronchitis, or combined emphysema and chronic bronchitis. Patients with obstructive diseases may have acute respiratory failure from any respiratory stress, such as infections or general anesthesia.

Occipital referring to the back part or bone of the head.

Occlude to close, obstruct, or join together.

Olfactory pertaining to the sense of smell.

Oncotic pressure the osmotic pressure of a colloid in solution, such as when there is a higher concentration of protein in the plasma on one side of a cell membrane than in the neighboring interstitial fluid.

Open pneumothorax the presence of air or gas in the chest as a result of an open wound in the chest wall.

Oral cavity [L, oralis, pertaining to the mough, cavum, cavity], the space within the mouth, containing the tongue and teeth.

Orthopnea a condition in which an individual is able to breathe most comfortably only in the upright position.

Osmosis the movement of a pure solvent such as water through a differentially permeable membrane from a solution that has a lower solute concentration to one that has a higher solute concentration. The membrane is impermeable to the solute but is permeable to the solvent. The rate of osmosis depends on the concentration of solute, the temperature of the solution, the electrical charge of the solute, and the difference between the osmotic pressures exerted by the solutions. Movement across the membrane continues until the concentrations of the solutions equalize.

Osmotic pressure pressure that develops when two solutions with different concentrations of solutes are separated by a semipermeable membrane.

Otitis media an inflammation or infection of the middle ear, common in early childhood. Acute otitis media is most often caused by Haemophilus influenzae, Moraxella catarrhalis, or Streptococcus pneumoniae. Chronic otitis media is usually caused by gram-negative bacteria such as Proteus, Klebsiella, and Pseudomonas. Allergy, Mycoplasma, and several viruses also may be causative factors. Otitis media is often preceded by an upper respiratory infection.

Oxygen consumption the amount of oxygen in milliliters per minute that the body requires for normal aerobic metabolism; normally about 250 mL/min.

Oxygen content total amount of oxygen in the blood.

Oxygen extraction ratio the amount of oxygen extracted by the peripheral tissues divided by the amount of oxygen delivered to the peripheral cells. Normally, about 25 percent. Also known as *oxygen coefficient ratio* or *oxygen utilization ratio*.

Oxygen toxicity a condition of oxygen overdosage that can result in pathologic tissue changes, such as retinopathy of prematurity or bronchopulmonary dysplasia. It can also decrease CO_2 drive to breathe.

Oxyhemoglobin the product of combining hemoglobin with oxygen. The loosely bound complex dissociates easily when the concentration of oxygen is low.

P

Palatine bones one of a pair of bones of the skull, forming the posterior part of the hard palate, part of the nasal cavity, and the floor of the orbit of the eie. It resembles a letter L and consists of horizontal and vertical parts and three processes.

Palatine process of the maxilla a thick, horizontal process of the maxilla. It forms the anterior three-quarters of the hard palate, with the horizontal plate of the palatine bone making up the rest.

Palatine tonsils palatine tonsil, one of a pair of almond-shaped masses of lymphoid tissue between the palatoglossal and palatopharyngeal arches on each side of the fauces.

Pallor an unnatural paleness or absence of color in the skin.

Papillitis an abnormal condition characterized by the inflammation of a papilla.

Paradoxic pertaining to a person, situation, statement, or act that may appear to have inconsistent or contradictory qualities or that may be true but appears to be absurd or unbelievable. Also paradoxical.

Parainfluenza a disease due to an acute respiratory infection caused by a parainfluenza virus. Parainfluenza usually occurs in children. The clinical picture can range from a relatively mild, influenza-like illness to bronchitis, croup, and pneumonia.

Parasympatholytic agent a substance or activity that reduces the activity of the parasympathetic nervous system. The parasympathetic nervous system is often colloquially described as the "feed and breed" or "rest and digest" portion of the autonomic nervous system. The parasympathetic nervous system becomes strongly engaged during or after a meal and during times when the body is at rest. The term *parasympatholytic* typically refers to the effect of a drug, although some poisons act to block the parasympathetic nervous system as well. Also called *anticholinergic drugs*.

Parasympathetic nervous system a division of the autonomic nervous system that is mediated by the release of acetylcholine and primarily involves the protection, conservation, and restoration of body resources.

Parenchyma essential parts of an organ that are concerned with its function.

Parietal layer pertaining to the outer wall of a cavity or organ.

Paroxysmal concerning the sudden, periodic attack or recurrence of symptoms of a disease.

Parturition the action or process of giving birth to offspring.

Pathogen any agent causing disease, especially a microorganism.

Peak flow meter an instrument for measuring the flow of air in the early part of forced expiration.

Perfusion passing of blood or fluid through a vascular bed.

Peribronchial located around the bronchi.

Pericarditis inflammation of the pericardium associated with trauma, malignant neoplastic disease, infection, uremia, myocardial infarction, collagen disease, or unknown causes.

Pericardium a fibroserous sac that surrounds the heart and the roots of the great vessels.

Peripheral airways small bronchioles on the outer sections of the lung.

Peripheral chemoreceptors extensions of the peripheral nervous system that respond to changes in blood molecule concentrations (such as oxygen or carbon dioxide) and help maintain cardiorespiratory homeostasis. They are located in the carotid and aortic bodies.

Peristalsis a progressive wave movement that occurs involuntarily in hollow tubes of the body, especially the intestines.

Perivascular located around a vessel, especially a blood vessel.

Permeable capable of allowing the passage of fluids or substances in solution.

Perpendicular plate the ethmoid bone (vertical plate) is a thin, flattened lamina, polygonal in form, that descends from the undersurface of the cribriform plate and assists in forming the septum of the nose; it is generally deflected a little to one side or the other. The anterior border articulates with the spine of the frontal bone and the crest of the nasal bones.

Persistent pulmonary hypertension of the neonate (PPHN) an elevated pulmonary vascular resistance in the newborn caused by a low P_{O_2} level. The infant's ductus arteriosus remains open as a result of this condition.

pH symbol for the logarithm of the reciprocal of the hydrogen ion concentration. The abbreviation for potential hydrogen, a scale representing the relative acidity of a solution in which a value of 7.0 is neutral, below 7.0 is acid, and above 7.0 is alkaline.

Phalanges the bones of the fingers and toes.

Pharyngotympanic (auditory) tubes a tube lined with mucous membrane that joins the nasopharynx and the middle ear cavity. It is normally closed but opens during yawning, chewing, and swallowing to allow equalization of the air pressure in the middle ear with atmospheric pressure.

Pharynx the throat, a tubular structure about 13 cm long that extends from the base of the skull to the esophagus and is situated immediately in front of the cervical vertebrae. The pharynx serves as a passageway for the respiratory and digestive tracts and changes shape to allow the formation of various vowel sounds. The pharybnx is composed of muscle, is lined with mucous membrane, and is divided into the nasopharynx, the oropharynx, and the laryngopharynx. It contains the opeings of the right and left auditory tubes, the openings of the two posterior nares, the fauces, the opening into the larynx, and the opening into the esophagus. It also contains the pharyngeal tonsils, the palatien tonsils, and the lingual tonsils. Also called throat.

Phosphate a salt of phosphoric acid. Phosphates are extremely important in living cells, particularly in the storage and use of energy and the transmission of genetic information within a cell and from one cell to another.

Photophobia abnormal sensitivity of the eyes to light.

Pituitary gland an endocrine gland suspended beneath the brain in the pituitary fossa of the sphenoid bone, supplying numerous hormones that govern many vital processes.

Plasma the watery straw-colored fluid part of the lymph and the blood in which the leukocytes, erythrocytes, and platelets are suspended. Plasma is made up of water, electrolytes, proteins, glucose, fats, bilirubin, and gases and is essential for carrying the cellular elements of the blood through the circulation, transporting nutrients, maintaining the acid-base balance of the body, and transporting wastes from the tissues. Plasma and interstitial fluid correspond closely in content and concentration of proteins; therefore, plasma is important in maintaining the osmotic pressure and the exchange of fluids and electrolytes between the capillaries and the tissues.

Platelet the smallest cells in the blood. They are formed in the red bone marrow and some are stored in the spleen. Platelets are disk shaped, contain no hemoglobin, and are essential for the coagulation of blood and in maintenance of hemostasis. Normally, between 140,000 and 340,000/mm^3.

Pleura (*pl. pleurae*) a delicate serous membrane enclosing the lung, composed of a single layer of flattened mesothelial cells resting on a delicate membrane of connective tissue. Beneath the membrane is a stroma of collagenous tissue containing yellow elastic fibers. The pleura divides into the visceral pleura, which covers the lungs, dipping into the fissures between the lobes, and the parietal pleura, which lines the chest wall, covers the diaphragm, and reflects over the structures of the mediastinum. The parietal and visceral pleurae are separated from each other by a small amount of fluid that acts as a lubricant as the lungs expand and contract during respiration. See also **pleural space**.

Pleural effusion an abnormal accumulation of fluid in the intrapleural spaces of the lungs. It is characterized by chest pain, dyspnea, adventitious lung sounds, and nonproductive cough. The fluid is an exudate or a transudate from inflamed pleural surfaces and may be aspirated or surgically drained. An exudate may result from pulmonary infarction, trauma, tumor, or infection, such as tuberculosis. The specific cause of the exudate is treated. Treatment of the effusion may include the administration of corticosteroids, diuretics, or vasodilators; oxygen therapy; intermittent positive-pressure breathing; or thoracentesis or use of a mobile system such as the Pleurx catheter.

Pleural space the potential space between the visceral and parietal layers of the pleurae. The space contains a small amount of fluid that acts as a lubricant, allowing the pleurae to slide smoothly over each other as the lungs expand and contract with respiration.

Pleurisy inflammation of the parietal pleura of the lungs. It is characterized by dyspnea and stabbing pain, leading to restriction of ordinary breathing with spasm of the chest on the affected side. A pleural friction rub may be heard on auscultation. Simple pleurisy with undetectable exudate is called fibrinous or dry pleurisy. Pleural effusion indicates extensive inflammation with considerable amounts of exudate in the pleural spaces. Common causes of pleurisy include bronchial carcinoma, lung or chest wall abscess, pneumonia, pulmonary infarction, and tuberculosis. The condition may result in permanent adhesions between the pleura and adjacent surfaces. Treatment consists of pain relief and therapy for the primary disease.

Pneumothorax a collection of air or gas in the pleural space, causing the lung to collapse.

Point of maximal intensity (PMI) the place where the apical pulse is palpated as strongest, often in the fifth intercostal space of the thorax, just medial to the left midclavicular line.

Polycythemia an increase in the number of erythrocytes in the blood caused by chronic hypoxemia secondary to pulmonary disease, heart disease, or prolonged exposure to high altitudes, or it may be idiopathic.

Polymer a compound formed by combining or linking a number of monomers, or small molecules. A polymer may be composed of many units of more than one type of monomer (a copolymer) or of many units of the same monomer (homopolymer).

Polysomography The polygraphic recording during sleep of multiple physiologic variables, both directly and indirectly related to the state and stages of sleep, to assess possible sleep disorders.

Pontine respiratory group a portion of the pontine respiratory centers that influences the respiratory components of the medulla. Neural impulses from the pneumotaxic center simultaneously cause (1) the depth of breathing to decrease and (2) the rate of breathing to increase by almost an equal amount. Some investigators believe the pneumotaxic center is closely related to the so-called panting center in animals such as dogs.

Positive end-expiratory pressure (PEEP) the alveolar pressure above atmospheric pressure that exists at the end of expiration. There are two types of PEEP: (1) extrinsic PEEP, which is the PEEP that is provided by a mechanical ventilator to help ensure that the alveoli remain open and referred to as applied PEEP, or (2) intrinsic PEEP, which is the PEEP that is secondary to an incomplete expiration (e.g., the incomplete expiration that occurs during an asthmatic episode) and referred to as intrinsic PEEP or auto-PEEP.

Posterior back part of something; toward the back.

Postural drainage drainage from the affected parts of the lungs are selected. Pillows and raised sections of the hospital bed are used to support or elevate parts of the body. The procedure is begun with the patient level, and the head is gradually lowered to a full Trendelenburg's position. Inhalation through the nose and exhalation through the mouth are encouraged. Simultaneously the nurse or other health care provider may use cupping and vibration over the affected area of the lungs to dislodge and mobilize secretions. The person is then helped to a position conducive to coughing and is asked to breathe deeply at least three times and to cough at least twice.

Premature ventricular complex (PVC) an arrhythmia characterized by ventricular depolarization occurring earlier than expected. It appears on the electrocardiogram as an early wide QRS complex without a preceding related P wave. PVCs may occur occasionally in a regular pattern or as several in sequence. They may be idiopathic or caused by stress, electrolyte imbalance, ischemia, hypoxemia, hypercapnia, ventricular enlargement, or a toxic reaction to drugs. Isolated PVCs are not clinically significant in healthy individuals, but they may produce decreased cardiac output in people with heart disease, and frequent PVCs may be a precursor of ventricular tachycardia or fibrillation.

Prerenal pertaining to the area in front of the kidney; pertaining to events occurring before reaching the kidney.

Pressoreceptor see **baroreceptor**.

Pressure a force, or stress, applied to a surface by a fluid or an object, usually measured in units of mass per unit of area, such as pounds per square inch.

Prognosis a prediction of the probable outcome of a disease based on the conditions of the person and the usual course of the disease as observed in similar situations.

Proliferate increasing or spreading at a rapid rate; the process or result of rapid reproduction.

Prostaglandins a group of fatty acid derivatives present in many organs that affect the cardiovascular system and smooth muscle and stimulate the uterus to contract.

Prostate a gland in males that surrounds the neck of the bladder and the deepest part of the urethra and produces a fluid that becomes part of semen.

Prostatic hypertrophy enlargement of the prostate gland.

Proton acceptor another name for a base, which is the opposite of an acid. A base is a negatively charged ion that will react with, or accept, a positively charged hydrogen ion. Because a hydrogen ion is a proton, the base is called a proton acceptor.

Proximal nearest the point of attachment, center of the body, or point of reference.

Pseudostratified columnar epithelia tissues formed by a single layer of cells that give the appearance of being made from multiple layers, especially when seen in cross section. The nuclei of these epithelial cells are at different levels, leading to the illusion of being stratified. However, this tissue is made of a single layer of cells, and while the cells do not share a common apical surface, each cell is in contact with the basement membrane. It is rare to find pseudostratified epithelia made from cuboidal or squamous cells; therefore, the most common subtype is pseudostratified columnar epithelium.

Pubic symphysis junction of the pubic bones, composed of fibrocartilage.

Pulmonary pertaining to the lungs or the respiratory system.

Pulmonary alveolus one of the numerous terminal air sacs in the lungs where oxygen and carbon dioxide are exchanged.

Pulmonary congestion an excessive accumulation of fluid in the lungs, usually associated with either an inflammation or congestive heart failure.

Pulmonary edema the accumulation of extravascular fluid in lung tissues and alveoli, caused most commonly by congestive heart failure. Serous fluid is pushed through the pulmonary capillaries into alveoli and quickly enters bronchioles and bronchi. The condition also may occur in barbiturate and opiate poisoning, diffuse infections, hemorrhagic pancreatitis, and renal failure or after a stroke, skull fracture, near-drowning, inhalation of irritating gases, and rapid administration of whole blood, plasma, serum albumin, or IV fluids.

Pulmonary embolus the blockage of a pulmonary artery by fat, air, tumor tissue, or a thrombus that usually arises from a peripheral vein (most frequently one of the deep veins of the legs). Predisposing factors include an alteration of blood constituents with increased coagulation, damage to blood vessel walls, and stagnation or immobilization, especially when associated with pregnancy and childbirth, congestive heart failure, polycythemia, or surgery. Pulmonary embolism is difficult to distinguish from myocardial infarction and pneumonia. It is characterized by dyspnea, anxiety, sudden chest pain, shock, and cyanosis. Pulmonary infarction, which often occurs within 24 hours after the formation of a pulmonary embolus, is further characterized by pleural effusion, hemoptysis, leukocytosis, fever, tachycardia, atrial arrhythmias, and striking distension of the neck veins. Analysis of blood gases reveals arterial hypoxia and hypocapnia. Pulmonary embolism is detected by chest radiographic films, pulmonary angiography, and radioscanning of the lung fields. Two thirds of patients with a massive pulmonary embolus die within 2 hours. Initial resuscitative measures include external cardiac massage, oxygen, vasopressor drugs, embolectomy, and correction of acidosis. The formation of further emboli is prevented by the use of anticoagulants, sometimes the use of streptokinase or urokinase, and also surgical intervention. Ambulation, exercise, and use of sequential compression devices on the lower extremities also are recommended for prevention. A vena cava filter may be inserted if pulmonary emboli recur.

Pulmonary emphysema a chronic obstructive disease of the lungs, marked by an overdistention of the alveoli and destruction of the supporting alveolar structure. See also **emphysema.**

Pulmonary hypoplasia incomplete development of the lungs, resulting in an abnormally low number or size of bronchopulmonary segments or alveoli. A congenital malformation, it most often occurs secondary to other fetal abnormalities that interfere with normal development of the lungs.

Pulmonary shunting that portion of the cardiac output that enters the left side of the heart without exchanging gases with alveolar gases.

Pulmonary surfactant one of certain lipoproteins that reduce the surface tension of pulmonary fluids, allowing the exchange of gases in the alveoli of the lungs and contributing to the elasticity of pulmonary tissue. **See also surfactant**

Pulmonary vascular resistance (PVR) pressure loss, per unit of blood flow, from the pulmonary artery to the left ventricle. The resistance in the pulmonary vascular bed against which the right ventricle must eject blood.

Pulse oximeter a device that measures the amount of saturated hemoglobin in the tissue capillaries by transmitting a beam of light through the tissue to a receiver. This noninvasive method of measuring the saturated hemoglobin is a useful screening tool for determining basic respiratory function. This cliplike device may be used on either the earlobe or the fingertip. As the amount of saturated hemoglobin alters the wavelengths of the transmitted light, analysis of the received light is translated into a percentage of oxygen saturation (SO_2) of the blood.

Pyelonephritis a diffuse pyogenic infection of the pelvis and parenchyma of the kidney.

R

Racemic epinephrine a mixture of dextro- and levo-isomers of epinephrine that, when nebulized, can be used in the treatment of croup and bronchiolitis. The drug is usually given with parenteral dexamethasone.

Rales see **crackle**.

Red blood cells mature red blood cell (also called erythrocytes); a biconcave disk about 7 µm in diameter that contains hemoglobin confined within a lipoid membrane. It is the major cellular element of the circulating blood and transports oxygen as its principal function. The number of cells per cubic millimeter of blood is usually maintained between 4.5 and 5.5 million in men and between 4.2 and 4.8 million in women. It varies with age, activity, and environmental conditions. For example, an increase to a level of 8 million/mm^3 can normally occur at over 10,000 feet above sea level. An erythrocyte normally lives for 110 to 120 days, when it is removed from the bloodstream and broken down by the reticuloendothelial system. New erythrocytes are produced at a rate of slightly more than 1% a day; thus a constant level is usually maintained. Acute blood loss, hemolytic anemia, or chronic oxygen deprivation may cause erythrocyte production to increase greatly. Erythrocytes originate in the marrow of the long bones. Maturation proceeds from a stem cell (promegaloblast) through the pronormoblast stage to the normoblast, the last stage before the mature adult cell develops.

Reflex an involuntary response to a stimulus.

Relative shunt a capillary shunt exists when blood flows from the right side of the heart to the left side without coming in contact with ventilated alveoli for gas exchange. Capillary shunting is commonly caused by (1) alveolar collapse or atelectasis, (2) alveolar fluid accumulation, or (3) alveolar consolidation. **See also Shunt-like effect**

Renal pertaining to the kidneys.

Renal dysplasia abnormal development of tissue in the kidneys.

Residual volume (RV) the amount of air remaining in the lungs after a maximal exhalation.

Resonance quality of the sound heard on percussion of a hollow structure such as the chest or abdomen.

Respiration the molecular exchange of oxygen and carbon dioxide within the body's tissue. Compare **ventilation**.

Respiratory acidosis a condition marked by high levels of carbon dioxide and a low pH in the blood, due to hypoventilation. Also called *acute ventilatory failure*.

Respiratory alkalosis a respiratory condition in which an increased alveolar ventilation (e.g., caused by an increased rate or depth of breathing) lowers the arterial carbon dioxide level below normal (35–45 mm Hg) and causes the blood pH to increase above the normal range (7.35–7.45).

Respiratory distress syndrome an acute lung disease of the newborn, characterized by airless alveoli, inelastic lungs, a respiration rate greater than 60 breaths per minute, nasal flaring, intercostal and subcostal retractions, grunting on expiration, and peripheral edema. The condition occurs most often in premature babies. It is caused by a deficiency of pulmonary surfactant, resulting in overdistended alveoli and at times hyaline membrane formation, alveolar hemorrhage, severe right-to-left shunting of blood, increased pulmonary resistance, decreased cardiac output, and severe hypoxemia. The disease is self-limited; the infant dies in 3 to 5 days or completely recovers with no aftereffects. Treatment includes measures to correct shock, acidosis, and hypoxemia and use of continuous positive airway pressure to prevent alveolar collapse. Also called hyaline membrane disease, idiopathic respiratory distress syndrome. Compare adult respiratory distress syndrome.

Resting membrane potential (RMP) the transmembrane voltage that exists when the heart muscle is at rest.

Restrictive lung disorder restrictive respiratory disease is caused by conditions that limit lung expansion, such as fibrothorax, obesity, a neuromuscular disorder, kyphosis, scoliosis, spondylitis, or surgical removal of lung tissue. Pregnancy causes a self-limiting restrictive disease in the third trimester. Characteristics of restrictive respiratory disease are decreased forced expired vital capacity and total lung capacity, with increased work of breathing and inefficient exchange of gases. Acute restrictive conditions are the most common pulmonary cause of acute respiratory failure. Infectious diseases include pneumonia and tuberculosis. ucus. Physical therapy measures, such as postural drainage and breathing exercises, can also dislodge secretions. Broad-spectrum antibiotics may be used prophylactically.

Rhinitis inflammation of the mucous membranes of the nose, usually accompanied by swelling of the mucosa and a nasal discharge.

Rhonchus (*pl. rhonchi*) an abnormal sound heard on auscultation of an airway obstructed by thick secretions, muscular spasm, neoplasm, or external pressure. The continuous rumbling sound is more pronounced during expiration and characteristically clears on coughing, whereas gurgles do not.

Rima glottidis also called rima glottidis, true glottis. a slitlike opening between the true vocal cords (plica vocalis).

S

Semipermeable permitting diffusion or flow of some liquids or solutes but preventing the transmission of others, usually in reference to a membrane.

Septal cartilage separates the left and right airways in the nose, dividing the two nostrils.

Septic pertaining to infection or contamination.

Septicemia systemic infection in which pathogens are present in the circulating blood, having spread from an infection in any part of the body. It is diagnosed by culture of the blood and is vigorously treated with antibiotics. Characteristically septicemia causes fever, chill, hypotension, prostration, pain, headache, nausea, or diarrhea. Also called *blood poisoning*.

Septum wall dividing two cavities.

Serotonin a potent vasoconstrictor that is present in platelets, gastrointestinal mucosa, mast cells, and carcinoid tumors.

Serum clear watery fluid, especially that moistening surfaces of serous membranes or exuded inflammation of any of those membranes; the fluid portion of the blood obtained after removal of the fibrin clot and blood cells; sometimes used as a synonym for antiserum.

Shunt to turn away from; to divert; an abnormal passage to divert flow from one route to another.

Shunt-like effect pulmonary capillary perfusion in excess of alveolar ventilation; commonly seen in patients with chronic obstructive lung disorders and alveolar-capillary diffusion defects. Also called *relative shunt*.

Sign an objective finding as perceived by an examiner, such as fever, a rash, or the whisper heard over the chest in pleural effusion. Many signs accompany symptoms; for example, erythema and a maculopapular rash are often seen with pruritus. Compare **symptom**.

Sinusitis an inflammation of one or more paranasal sinuses.

Slow vital capacity (SVC) the maximum volume of air that can be slowly exhaled after a maximal inspiration.

Smooth muscle muscle tissue that lacks cross-striations on its fibers, is involuntary in action, and is found principally in visceral organs.

Soft palate the structue composed of mucous membrane, muscular fibers, and mucous glands, suspended from the posterior border of the hard palate forming the roof of the mouth. When the soft palate rises, as in swallowing and in sucking, it separates the nasal cavity and the nasopharynx from the posterior part of the oral cavity and the oral part of the pharynx. The posterior border of the soft palate hangs like a curtain between the mouth and the pharynx. Suspended from it is the conical, pendulous, palatine uvula. Arching laterally from the base of the uvula are the two curved musculomembranous pillars of the fauces.

Somatic nerve nerve that innervates somatic structures, that is, those constituting the body wall and extremities.

Somnolence the condition of being sleepy or drowsy.

Spasm involuntary sudden movement or convulsive muscular contraction.

Sputum substance expelled by coughing or clearing the throat that may contain a variety of materials from the respiratory tract, including one or more of the following: cellular debris, mucus, blood, pus, caseous material, and microorganisms.

Stasis stagnation of normal flow of fluids, as of the blood, urine, or intestinal mechanism. A disorder in which the normal flow of a fluid through a vessel of the body is slowed or halted.

Stent a rod or threadlike device for supporting tubular structures during surgical anastomosis or for holding arteries open during angioplasty.

Stratified squamous epithelium consists of squamous (flattened) epithelial cells arranged in layers upon a basal membrane. Only one layer is in contact with the basement membrane; the other layers adhere to one another to maintain structural integrity.

Stroke volume amount of blood ejected by the ventricle at each beat.

Strong base a base that is completely dissociated in an aqueous solution aqueous. These compounds ionize in water to yield one or more hydroxide ion (OH^-) per molecule of base.

Subcutaneous under the skin.

Sulfonamide one of a large group of synthetic, bacteriostatic drugs that are effective in treating infections caused by many gram-negative and gram-positive microorganisms.

Superior situated above or oriented toward a higher place, as the head is superior to the torso.

Superior vena cava venous trunk draining blood from the head, neck, upper extremities, and chest.

Surfactant an agent, such as soap or detergent, dissolved in water to reduce its surface tension or the tension at the interface between the water and another liquid. Certain lipoproteins reduce the surface tension of pulmonary fluids, allowing the exchange of gases in the alveoli of the lungs and contributing to the elasticity of the pulmonary tissue. Also called *pulmonary surfactant*.

Sympathetic nervous system a division of the autonomic nervous system that accelerates the heart rate, constricts blood vessels, and raises blood pressure.

Sympathomimetic producing effects resembling those resulting from stimulation of the sympathetic nervous system.

Sympathomimetic agent stimulant compounds that mimic the effects of endogenous agonists of the sympathetic nervous system. The primary endogenous agonists of the sympathetic nervous system are the catecholamines (i.e., epinephrine [adrenaline], norepinephrine [noradrenaline], and dopamine), which function as both neurotransmitters and hormones. Sympathomimetic drugs are used to treat cardiac arrest and low blood pressure, or even delay premature labor, among other things. Also known as *adrenergic drugs* and *adrenergic amines*.

Symptom a subjective indication of a disease or a change in condition as perceived by the patient. For example, the halo symptom of glaucoma is seen by the patient as colored rings around a single light source. Many symptoms are accompanied by objective signs, such as pruritus, which is often reported with erythema and a maculopapular eruption on the skin. Some symptoms may be objectively confirmed, such as numbness of the body part, which may be confirmed by absence of response to a pin prick. Compare **sign**.

Systemic pertaining to the whole body rather than to one of its parts.

Systemic reaction whole body response to a stimulus.

Systemic system the general blood circulation of the body, not including the lungs.

Systole that part of the heart cycle in which the heart is in contraction.

Systolic pressure maximum blood pressure; occurs during contraction of the ventricle.

T

Tachycardia an abnormal circulatory condition in which the myocardium contracts regularly but at a rate of greater than 100 beats per minute.

Tachypnea a rapid rate of breathing.

Tension pneumothorax the presence of air in the pleural space when pleural pressure exceeds alveolar pressure, caused by a rupture through the chest wall or lung parenchyma associated with the valvular opening. Air passes through the valve during coughing but cannot escape on exhalation. Unrelieved pneumothorax can lead to respiratory arrest.

The barometric pressure (PB) the pressure exerted by the weight of the atmosphere. The average atmospheric pressure at sea level is approximately 14.7 pounds per square inch. With increasing altitude the pressure decreases: at 30,000 feet, approximately the height of Mt. Everest, the air pressure is 4.3 pounds per square inch. Also called atmospheric pressure.

Thoracentesis the surgical perforation of the chest wall and pleural space with a needle to aspirate fluid for diagnostic or therapeutic purposes or to remove a specimen for biopsy. The procedure is usually performed using local anesthesia, with the patient in an upright position. Thoracentesis may be used to aspirate fluid to treat pleural effusion or to collect fluid samples for culture or examination. Also called thoracocentesis.

Thoracolumbar relating to the thoracic and lumbar portions of the vertebral column.

Thrombocyte combining form meaning "platelet": *thrombocytopenia, thrombocytosis*.

Tidal volume the volume of air that normally moves into and out of the lungs in one quiet breath; the measured inspired or expired volume of gas moved in one breath.

Tone that state of a body or any of its organs or parts in which the functions are healthy and normal.

Tongue the principal organ of the sense of taste that also assists in the mastication and deglutition of food. It is located in the floor of the mouth within the curve of the mandible. Its root is connected to the hyoid bone posteriorly. It is also connected to the epiglottis, soft palate, and pharynx. The apex of the tongue rests anteriorly against the lingual surfaces of the lower incisors. The mucous membrane connecting the tongue to the mandible reflects over the floor of the mouth to the lingual surface of the gingiva and in the midline of the floor is raised into a vertical fold. The dorsum of the tongue is divided into symmetric halves by a median sulcus, which ends posteriorly in the foramen cecum. A shallow sulcus terminalis runs from this foramen laterally and forward on either side to the margin of the organ. From the sulcus the anterior two thirds of the tongue are covered with papillae. The posterior third is smoother and contains numerous mucous glands and lymph follicles. The use of the tongue as an organ of speech is not anatomic but a secondary acquired characteristic.

Total lung capacity the maximum amount of air that the lung can accommodate.

Total oxygen delivery the total amount of oxygen delivered or transported to the peripheral tissues.

Transairway pressure the barometric pressure difference between the mouth pressure and the alveolar pressure.

Transmural pressure the pressure difference that occurs across the airway wall.

Transrespiratory pressure (Prs) the difference between the barometric (atmospheric) pressure (PB) and the alveolar pressure (Palv). Also called transairway pressure.

Transient passing especially quickly into and out of existence; passing through or by a place with only a brief stay.

Transpulmonary pressure the difference between the alveolar pressure and the pleural pressure.

Transthoracic pressure the difference between the alveolar pressure and the body surface pressure.

Tricuspid valve a valve with three main cusps situated between the right atrium and right ventricle of the heart. The tricuspid valve includes the ventral, dorsal, and medial cusps. The cusps are composed of strong fibrous tissue and are anchored to the papillary muscles of the right ventricle by several tendons. As the right and left ventricles relax during the diastolic phase of the heartbeat, the tricuspid valve opens, allowing blood to flow into the ventricle. In the systolic phase of the heartbeat, both blood-filled ventricles contract, pumping out their contents, while the tricuspid and mitral valves close to prevent any backflow.

Trimester one of the three periods of approximately 3 months into which pregnancy is divided.

True shunt see **absolute shunt**.

U

Unilateral renal agenesis failure of one of the kidneys to develop.

Upper airway the upper airways consist of the nose, oral cavity, pharynx, and larynx.

Uvula an opening in the arch connects the mouth with the oropharynx; the uvula is suspended from the middle of the posterior border of the arch.

V

Vagus nerve the tenth cranial nerve. It is a mixed nerve, having motor and sensory functions and a wider distribution than any of the other cranial nerves.

Vallecula epiglottica a furrow between the glossoepiglottic folds of each side of the posterior oropharynx. Also called (informal) vallecula.

Vascular relating to or containing blood vessels.

Vascular system the circulatory network composed of two major subdivisions: the systemic system and the pulmonary system.

Vasoconstriction decrease in the caliber of blood vessels.

Vasodilation widening of blood vessels, especially the small arteries and arterioles.

Vasomotor tone the state of vascular contraction.

Vein any one of the many vessels that convey blood from the capillaries as part of the pulmonary venous system, the systemic venous network, and the portal venous complex. Most of the veins of the body are systemic veins that convey blood from the whole body (except the lungs) to the right atrium of the heart. Each vein is a macroscopic structure enclosed in three layers of different kinds of tissue homologous with the layers of the heart. The outer tunica adventitia of each vein is homologous with the epicardium, the tunica media with the myocardium, and the tunica intima with the endocardium. Deep veins course through the more internal parts of the body, and superficial veins lie near the surface, where many of them are visible through the skin. Veins have thinner coatings and are less elastic than arteries and collapse when cut. They also contain semilunar valves at various intervals to control the direction of the blood flow back to the heart.

Venous pertaining to a vein or veins.

Venous admixture the mixing of shunted, non-reoxygenated blood with reoxygenated blood distal to the alveoli.

Venous return the amount of blood returning to the atria of the heart.

Ventilation the mechanical movement of air into and out of the lungs in a cyclic fashion. It is the mechanism by which oxygen is carried from the atmosphere to the alveoli and by which carbon dioxide is carried from the lungs to the atmosphere. Compare **respiration**.

Ventilation-perfusion ratio the relationship of the overall alveolar ventilation (L/min) to the overall pulmonary blood flow (L/min). The normal ventilation-perfusion ratio is 4:5, or 0.8.

Ventral pertaining to the anterior portion or front of the body.

Ventricle either of two lower chambers of the heart.

Venule any one of the small blood vessels that gather blood from the capillary plexuses and anastomose to form the veins.

Vestibule a space or a cavity that serves as the entrance to a passageway, such as the vestbule of the ear.

Vibrissae any of the stiff hairs that are located on the face and especially about the snout of many mammals and typically serve as tactile organs; a similar stiff tactile hair growing elsewhere on some mammals (as in a small tuft at the wrist); any of the coarse hairs growing within the nostrils of humans that serve to impede the inhalation of particulate matter.

Viscera (*sing. viscus*) the internal organs enclosed within a body cavity, including the abdominal, thoracic, pelvic, and endocrine organs.

Viscosity stickiness or gumminess; internal friction resistance offered by a fluid to change of form or relative position of its particles due to attraction of molecules to each other.

Viscous sticky; gummy; gelatinous.

Vital capacity the maximum volume of air that can be exhaled after a maximal inspiration.

Volume percent (vol%) the number of milliliters (mL) of a substance contained in 100 mL of another substance. For example, under normal conditions there are about 20 mL of oxygen in every 100 mL of arterial blood—or 20 vol% oxygen.

Vomer the plow-shaped bone forming the posterior and inferior part of the nasal septum and having two surfaces and four borders.

W

Weak base a base that only partially dissociates into its ions in water. Ammonia is a good example of a weak base.

Wenckebach phenomenon named for Karel F. Wenckebach, Dutch-Austrian physician (1864–1940), a form of second-degree atrioventricular block with a progressive beat-to-beat prolongation of the PR interval, finally resulting in a nonconducting P wave. At this point the sequence recurs and is referred to as Wenckebach periodicity. Also called *Mobitz I* and *type I AV block*.

Wheeze a form of rhonchi characterized by a high-pitched or low-pitched musical quality. It is caused by a high-velocity flow of air passing through a narrowed airway and is heard during both inspiration and expiration. It may be caused by bronchospasm, inflammation, or obstruction of the airway by a tumor or foreign body. Wheezes are associated with asthma and chronic bronchitis. Unilateral wheezes are characteristic of bronchogenic carcinoma, foreign bodies, and inflammatory lesions. In asthma expiratory wheezing is more common, although inspiratory and expiratory wheezes are heard. Compare **crackle**, **rhonchus**.

White blood cell a blood cell that participates in immunity and inflammation. Five categories of leukocytes are classified by nuclear appearance and the presence or absence of granules in the cytoplasm. Lymphocytes have no granules or a few scattered azurophilic granules. The granulocytes are monocytes, neutrophils, basophils, and eosinophils. White cells are able to pass through endothelial gap junctions by diapedesis and migrate by ameboid movements. Leukocytes measure 8–20 µm in diameter. Normal WBC counts vary from 4500–11,500 leukocytes/µL. Leukocytes function as phagocytes of bacteria, fungi, and viruses; detoxifiers of proteins that may result from allergic reactions and cellular injury; and immune system cells. Also called *leukocyte* and *white corpuscle*.

APPENDIX

Symbols and Abbreviations

The symbols and abbreviations listed below are commonly used in respiratory physiology.

Primary Symbols

Gas Symbols		Blood Symbols	
P	Pressure	Q	Blood volume
V	Gas volume	$\dot{Q}$	Blood flow
$\dot{V}$	Gas volume per unit of time, or flow	C	Content in blood
F	Fractional concentration of gas	S	Saturation

Secondary Symbols

Gas Symbols		Blood Symbols	
I	Inspired	a	Arterial
E	Expired	c	Capillary
A	Alveolar	v	Venous
T	Tidal	$\bar{v}$	Mixed venous
D	Dead space		

Abbreviations

Lung Volume	
VC	Vital capacity
IC	Inspiratory capacity
IRV	Inspiratory reserve volume
ERV	Expiratory reserve volume
FRC	Functional residual capacity
RV	Residual volume
TLC	Total lung capacity

continued

Abbreviations (Continued)

Lung Volume

RV/TLC(%)	Residual volume to total lung capacity ratio, expressed as a percentage
V_T	Tidal volume
$\dot{V}_A$	Alveolar ventilation
V_D	Dead space ventilation
V_L	Actual lung volume

Spirometry

FVC	Forced vital capacity with maximally forced expiratory effort
FEV_T	Forced expiratory volume timed
$FEF_{200-1200}$	Average rate of airflow between 200 and 1200 mL of the FVC
$FEF_{25\%-75\%}$	Forced expiratory flow during the middle half of the FVC (formerly called the maximal midexpiratory flow or MMF)
PEFR	Maximum flow rate that can be achieved
$\dot{V}_{\max x}$	Forced expiratory flow related to the actual volume of the lungs as denoted by subscript *x*, which refers to the amount of lung volume remaining when measurement is made
MVV	Maximal voluntary ventilation as the volume of air expired in a specified interval

Mechanics

C_L	Lung compliance; volume change per unit of pressure change
R_{aw}	Airway resistance; pressure per unit of flow

Diffusion

DL_{CO}	Diffusing capacity of carbon monoxide (CO)

Blood Gases

PA_{O_2}	Alveolar oxygen tension
PC_{O_2}	Pulmonary capillary oxygen tension
Pa_{O_2}	Arterial oxygen tension
$P\bar{v}_{O_2}$	Mixed venous oxygen tension
PA_{CO_2}	Alveolar carbon dioxide tension
PC_{CO_2}	Pulmonary capillary carbon dioxide tension
Pa_{CO_2}	Arterial carbon dioxide tension
Sa_{O_2}	Arterial oxygen saturation
$S\bar{v}_{O_2}$	Mixed venous oxygen saturation
pH	Negative logarithm of the H^+ concentration used as a positive number
HCO_3^-	Plasma bicarbonate concentration
mEq/L	The number of grams of solute dissolved in a normal solution
Ca_{O_2}	Oxygen content of arterial blood
Cc_{O_2}	Oxygen content of capillary blood

$C\bar{v}_{O_2}$	Oxygen content of mixed venous blood
$\dot{V}/\dot{Q}$	Ventilation-perfusion ratio
$\dot{Q}s/\dot{Q}_T$	Shunt fraction
$\dot{Q}_T$	Total cardiac output

Oxygen Transport Studies

$C(a - \bar{v})_{O_2}$	Arterial-venous oxygen content difference
$\dot{V}O_2$	Oxygen consumption (oxygen uptake)
O_2ER	Oxygen extraction ratio
DO_2	Total oxygen delivery

Hemodynamic Measurement Abbreviations

Direct Measurements

CVP	Central venous pressure
RAP	Right atrial pressure
$\overline{PAP}$	Mean pulmonary artery pressure
PCWP	Pulmonary capillary wedge pressure
PAW	Pulmonary artery wedge
PAO	Pulmonary artery occlusion
CO	Cardiac output

Indirect Measurements

SV	Stroke volume
SVI	Stroke volume index
CI	Cardiac index
RVSWI	Right ventricular stroke work index
LVSWI	Left ventricular stroke work index
PVR	Pulmonary vascular resistance
SVR	Systemic vascular resistance

Metric Measurement Abbreviations

Linear Measurements

m	meter
cm	centimeter (m × 10^{-2})
mm	millimeter (m × 10^{-3})
µm	micrometer (m × 10^{-6})

Volume Measurements

L	liter
dL	deciliter (1×10^{-1})
mL	milliliter (1×10^{-3})
μL	microliter (1×10^{-6})
nL	nanoliter (1×10^{-9})

Weight Measurements

g	gram
mg	milligram ($g \times 10^{-3}$)
μg	microgram ($g \times 10^{-6}$)
ng	nanogram ($g \times 10^{-9}$)

APPENDIX II

Units of Measurement

Metric Length

Meter	Centimeter	Millimeter	Micrometer	Nanometer
1	100	1000	1,000,000	1,000,000,000
.01	1	10	10,000	10,000,000
.001	.1	1	1000	1,000,000
.000001	.0001	.001	1	1000
.000000001	.0000001	.000001	.001	1

Metric Volumes

Liter	Centiliter	Milliliter	Microliter	Nanoliter
1	100	1000	1,000,000	1,000,000,000
.01	1	10	10,000	10,000,000
.001	.1	1	1000	1,000,000
.000001	.0001	.001	1	1000
.000000001	.0000001	.000001	.001	1

Metric Weight

Grams	Centigrams	Milligrams	Micrograms	Nanograms
1	100	1000	1,000,000	1,000,000,000
.01	1	10	10,000	10,000,000
.001	.1	1	1000	1,000,000
.000001	.0001	.001	1	1000
.000000001	.0000001	.000001	.001	1

Weight Conversions (Metric and Avoirdupois)

Grams	Kilograms	Ounces	Pounds
1	.001	.0353	.0022
1000	1	35.3	2.2
28.35	.02835	1	$\frac{1}{16}$
454.5	.4545	16	1

Weight Conversions (Metric and Apothecary)

Grams	Milligrams	Grains	Drams	Ounces	Pounds
1	1000	15.4	.2577	.0322	.00268
.001	1	.0154	.00026	.0000322	.00000268
.0648	64.8	1	$\frac{1}{60}$	$\frac{1}{480}$	$\frac{1}{5760}$
3.888	3888	60	1	$\frac{1}{8}$	$\frac{1}{96}$
31.1	31104	480	8	1	$\frac{1}{12}$
373.25	373248	5760	96	12	1

Approximate Household Measurement Equivalents (Volume)

1 tsp = 5 mL
1 tbsp = 3 tsp = 15 mL
1 fl oz = 2 tbsp = 6 tsp = 30 mL
1 cup = 8 fl oz = 240 mL
1 pt = 2 cups = 16 fl oz = 480 mL
1 qt = 2 pt = 4 cups = 32 fl oz = 960 mL
1 gal = 4 qt = 8 pt = 16 cups = 128 fl oz = 3840 mL

Weight

Metric	Approximate Apothecary Equivalents
Grams	**Grains**
.0002	$\frac{1}{300}$
.0003	$\frac{1}{200}$
.0004	$\frac{1}{150}$
.0005	$\frac{1}{120}$
.0006	$\frac{1}{100}$
.001	$\frac{1}{60}$
.002	$\frac{1}{30}$
.005	$\frac{1}{12}$
.010	$\frac{1}{6}$
.015	$\frac{1}{4}$
.025	$\frac{3}{8}$
.030	$\frac{1}{2}$
.050	$\frac{3}{4}$
.060	1
.100	$1\frac{1}{2}$
.120	2
.200	3
.300	5
.500	$7\frac{1}{2}$
.600	10
1	15
2	30
4	60

Liquid Measure

Metric	Approximate Apothecary Equivalents
Milliliters	
1000	1 quart
750	$1\frac{1}{2}$ pints
500	1 pint
250	8 fluid ounces
200	7 fluid ounces
100	$3\frac{1}{2}$ fluid ounces
50	$1\frac{3}{4}$ fluid ounces
30	1 fluid ounce

continued

Liquid Measure (Continued)

Metric	Approximate Apothecary Equivalents
15	4 fluid drams
10	$2\frac{1}{2}$ fluid drams
8	2 fluid drams
5	$1\frac{1}{4}$ fluid drams
4	1 fluid dram
3	45 minims
2	30 minims
1	15 minims
0.75	12 minims
0.6	10 minims
0.5	8 minims
0.3	5 minims
0.25	4 minims
0.2	3 minims
0.1	$1\frac{1}{2}$ minims
0.06	1 minim
0.05	$\frac{3}{4}$ minim
0.03	$\frac{1}{2}$ minim

Volume Conversions (Metric and Apothecary)

Milliliters	Minims	Fluid Drams	Fluid Ounces	Pints
1	16.2	.27	.0333	.0021
.0616	1	$\frac{1}{60}$	$\frac{1}{480}$	$\frac{1}{7680}$
3.697	60	1	$\frac{1}{8}$	$\frac{1}{128}$
29.58	480	8	1	$\frac{1}{16}$
473.2	7680	128	16	1

Liters	Gallons	Quarts	Fluid Ounces	Pints
1	.2642	1.057	33.824	2.114
3.785	1	4	128	8
.946	$\frac{1}{4}$	1	32	2
.473	$\frac{1}{8}$	$\frac{1}{2}$	16	1
.0296	$\frac{1}{128}$	$\frac{1}{32}$	1	$\frac{1}{16}$

Length Conversions (Metric and English System)

Unit	Millimeters	Centimeters	Inches	Feet	Yards	Meters
1Å =	$\frac{1}{10,000,000}$	$\frac{1}{100,000,000}$	$\frac{1}{254,000,000,000}$	$\frac{1}{3,050,000,000}$	$\frac{1}{9,140,000,000}$	$\frac{1}{10,000,000,000}$
1 nm =	$\frac{1}{1,000,000}$	$\frac{1}{10,000,000}$	$\frac{1}{25,400,000}$	$\frac{1}{305,000,000}$	$\frac{1}{914,000,000}$	$\frac{1}{1,000,000,000}$
1 µm =	$\frac{1}{1000}$	$\frac{1}{10,000}$	$\frac{1}{25,400}$	$\frac{1}{305,000}$	$\frac{1}{914,000}$	$\frac{1}{1,000,000}$
1 mm =	1.0	0.1	0.03937	0.00328	0.0011	0.001
1 cm =	10.0	1.0	0.3937	0.03281	0.0109	0.01
1 in. =	25.4	2.54	1.0	0.0833	0.0278	0.0254
1 ft =	304.8	30.48	12.0	1.0	0.333	0.3048
1 yd =	914.40	91.44	36.0	3.0	1.0	0.9144
1 m =	1000.0	100.0	39.37	3.2808	1.0936	1.0

APPENDIX

Poiseuille’s Law

Poiseuille’s Law for Flow Rearranged to a Simple Proportionality

$\dot{V} \simeq \Delta P r^4$, or rewritten as $\dfrac{\dot{V}}{r^4} \simeq \Delta P$.

When ΔP remains constant, then

$$\frac{\dot{V}_1}{r_1^{\,4}} \simeq \frac{\dot{V}_2}{r_2^{\,4}}$$

Example 1. If the radius (r_1) is decreased to one-half its previous radius ($r_2 = \frac{1}{2}r_1$), then

$$\frac{\dot{V}_1}{r_1^{\,4}} \simeq \frac{\dot{V}_2}{\left(\frac{1}{2}r_1\right)^4}$$

$$\frac{\dot{V}_1}{r_1^{\,4}} \simeq \frac{\dot{V}_2}{\left(\frac{1}{16}r_1\right)^4}$$

$$(r_1^{\,4})\frac{\dot{V}_1}{r_1^{\,4}} \simeq (r_1^{\,4})\frac{\dot{V}_2}{\left(\frac{1}{16}\right)r_1^{\,4}}$$

$$\dot{V}_1 \simeq \frac{\dot{V}_2}{\frac{1}{16}}$$

$$\left(\frac{1}{16}\right)\dot{V}_1 \simeq \left(\frac{1}{16}\right)\frac{\dot{V}_2}{\frac{1}{16}}$$

$$\left(\frac{1}{16}\right)\dot{V}_1 \simeq \dot{V}_2$$

and gas flow ($\dot{V}_1$) is reduced to $\frac{1}{16}$ its original flow rate [$\dot{V}_2 \simeq \left(\frac{1}{16}\right)\dot{V}_1$].

Example 2. If the radius (r_1) is decreased by 16% ($r_2 = r_1 - 0.16r_1 = 0.84r_1$), then

$$\frac{\dot{V}_1}{r_1^{\,4}} \simeq \frac{\dot{V}_2}{r_2^{\,4}}$$

$$\frac{\dot{V}_1}{r_1^{\,4}} \simeq \frac{\dot{V}_2}{(0.84r_1)^4}$$

$$\dot{V}_2 \simeq \frac{(0.84r_1)^4\dot{V}_1}{r_1^{\,4}}$$

$$\dot{V}_2 \simeq \frac{0.4979\,\cancel{r_1^4}\,\dot{V}_1}{\cancel{r_1^4}}$$

$$\dot{V}_2 \simeq \tfrac{1}{2}\dot{V}_1$$

and the flow rate ($\dot{V}_1$) would decrease to one-half the original flow rate ($\dot{V}_2 \simeq \frac{1}{2}\dot{V}_1$).

Poiseuille's Law for Pressure Rearranged to a Simple Proportionality

$$P \simeq \frac{\dot{V}}{r^4}, \text{ or rewritten as } P \cdot r^4 \simeq \dot{V}$$

when $\dot{V}$ remains constant, then

$$P_1 \cdot r_1^4 \simeq P_2 \cdot r_2^4$$

Example 1. If the radius (r_1) is reduced to one-half its original radius $\left[r_2 = \left(\frac{1}{2}\right)r_1\right]$, then

$$P_1 \cdot r_1^4 \simeq P_2 \cdot r_2^4$$

$$P_1 \cdot r_1^4 \simeq P_2\left[\left(\frac{1}{2}\right)r_1\right]^4$$

$$P_1 \cdot r_1^4 \simeq P_2 \cdot \left(\frac{1}{16}\right)r_1^4$$

$$\frac{P_1 \cdot \cancel{r_1^4}}{\cancel{r_1^4}} \simeq \frac{P_2 \cdot \left(\frac{1}{16}\right)\cancel{r_1^4}}{\cancel{r_1^4}}$$

$$P_1 \simeq P_2 \cdot \left(\frac{1}{16}\right)$$

$$16\,P_1 \simeq \cancel{16} \cdot P_2 \cdot \left(\frac{1}{\cancel{16}}\right)$$

$$16\,P_1 \simeq P_2$$

and the pressure (P_1) will increase to 16 times its original level ($P_2 \simeq 16 \cdot P_1$).

Example 2. If the radius (r_1) is decreased by 16% ($r_2 = r_1 - 0.16r_1 = 0.84r_1$), then

$$P_1 \cdot r_1^4 \simeq P_2 \cdot r_2^4$$

$$P_1 \cdot r_1^4 \simeq P_2\,(0.4979)r_1^4$$

$$\frac{P_1\cancel{r_1^4}}{(0.4979)\cancel{r_1^4}} = P_2$$

$$2\,P_1 = P_2$$

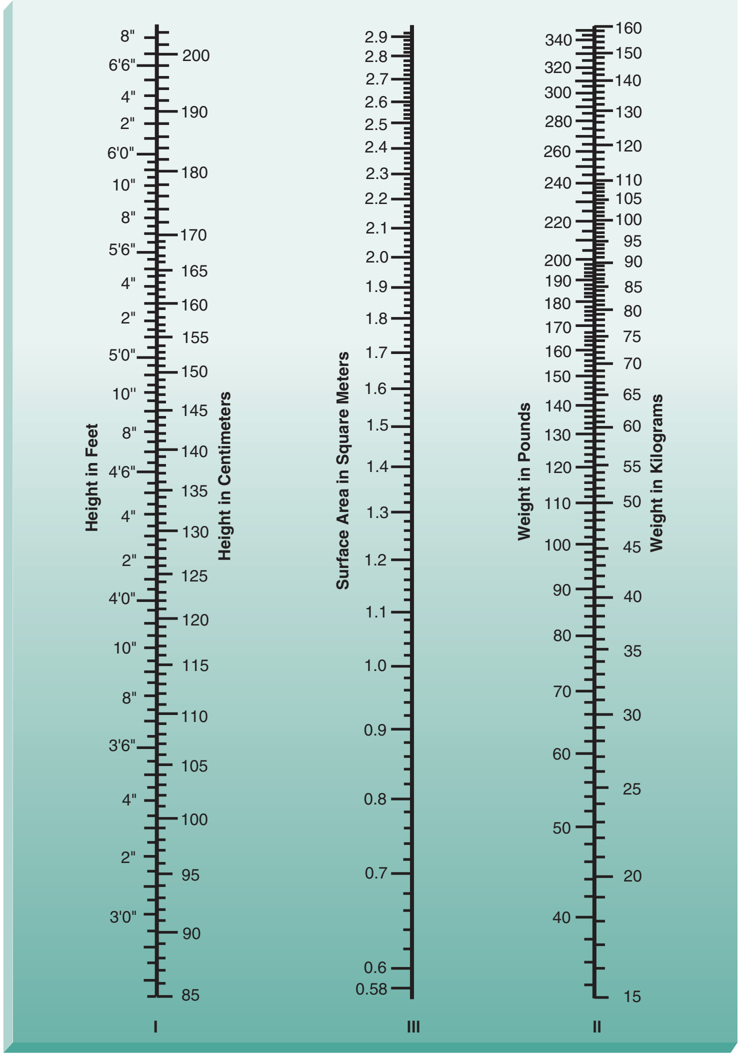
and the pressure (P_1) would increase to twice its original pressure ($P_2 \simeq 2 \cdot P_1$).

APPENDIX IV

DuBois Body Surface Chart

Directions

To find body surface of a patient, locate the height in inches (or centimeters) on Scale I and the weight in pounds (or kilograms) on Scale II and place a straightedge (ruler) between these two points which will intersect Scale III at the patient’s surface area.

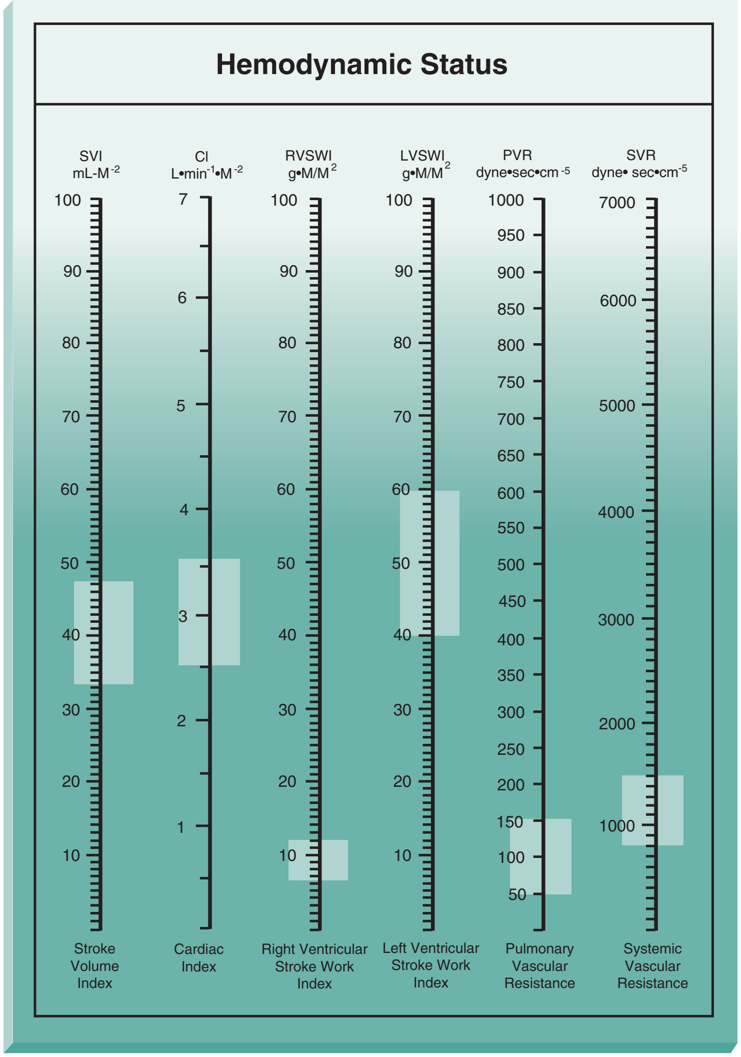


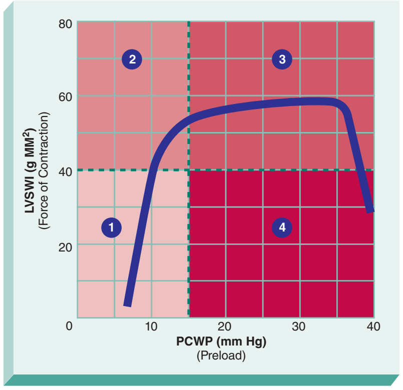
Adapted from DuBois, Eugene F. *Basal Metabolism in Health and Disease*. Philadelphia, PA: Lea and Febiger, 1924.

APPENDIX V

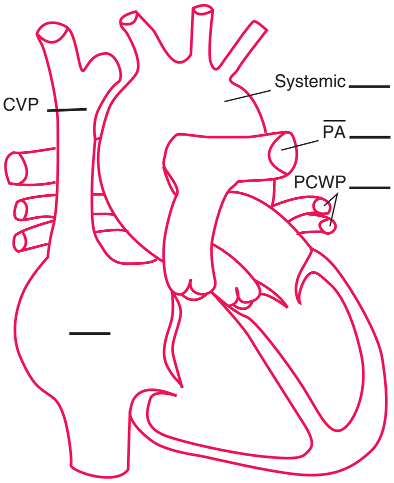
Cardiopulmonary Profile

A representative example of a cardiopulmonary profile sheet used to monitor the critically ill patient. Refer to Chapters 5, 6, and 7 for explanations of the various components presented in this sample cardiopulmonary profile. Areas shaded in pink represent normal ranges.





Quadrant 1: Hypovolemia
Quadrant 2: Optimal Function
Quadrant 3: Hypervolemia
Quadrant 4: Cardiac Failure



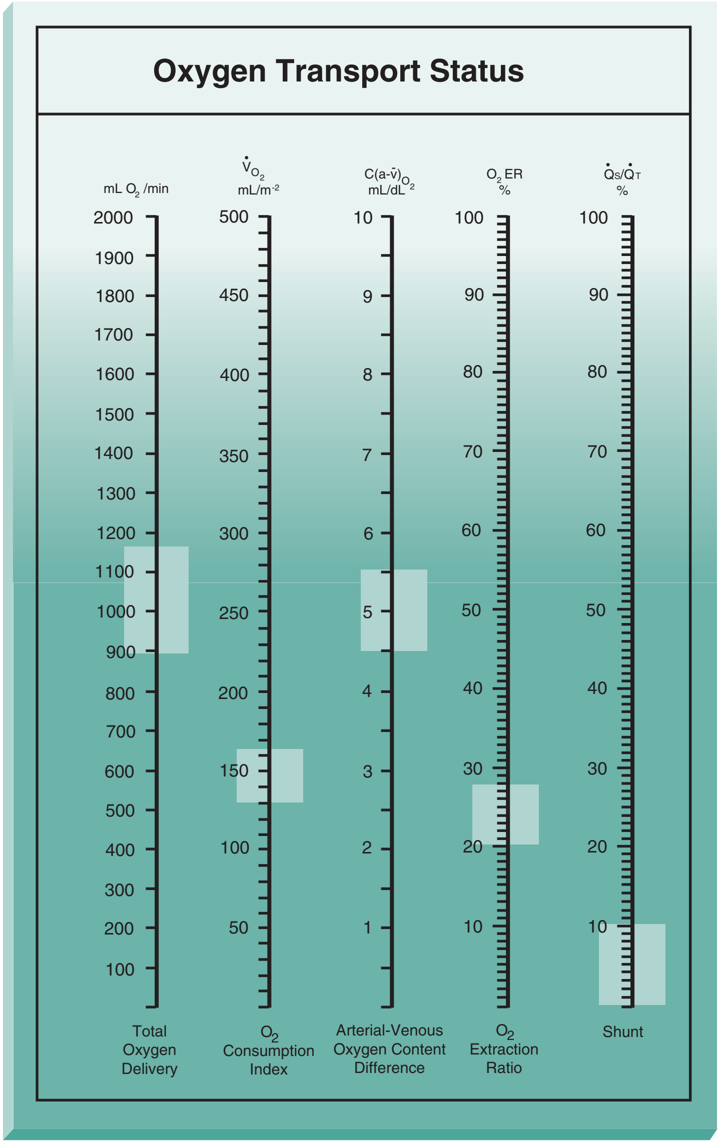
Temperature: ____________________

Heart Rate: ____________________

Cardiac Output: ____________________

Medications: ____________________

____



Blood Gas Values

pH ____________________

Pa_{CO_2} ____________________

HCO_3^- ____________________

Pa_{O_2} ________________ $P\bar{v}_{O_2}$ ________________

Sa_{O_2} ________________% $S\bar{v}_{O_2}$ ________________%

FI_{O_2} ________________ Hb ________________

Mode(s) of Ventilatory Support: ____________________

____

____

____

____

____

Shaded areas represent normal ranges.

Patient's Name ____________________

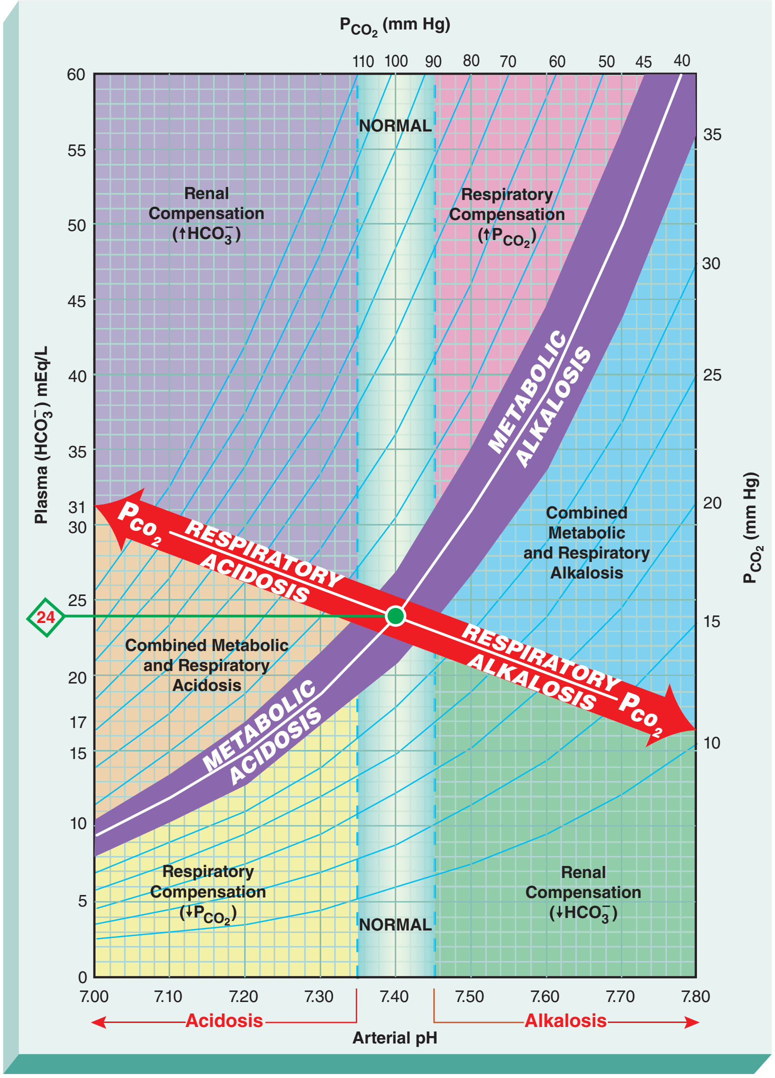
Date ____________________

Time ____________________

APPENDIX VI

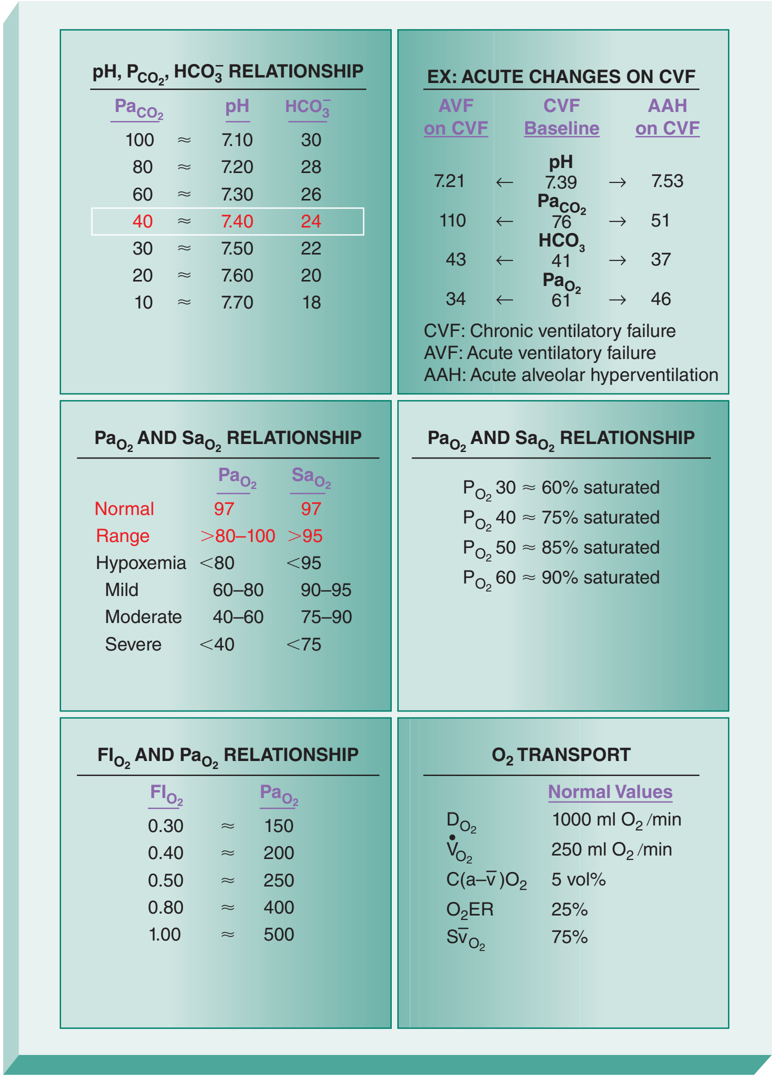
P_{CO_2}/HCO_3^-/pH Nomogram

Nomogram—Slide 1



Cut out the above two-sided nomogram and have it laminated for use as a handy, pocket-sized reference tool. Refer to Chapter 7 on how to use the nomogram in the clinical setting.

Nomogram—Slide 2



pH, P_{CO_2}, HCO_3^- RELATIONSHIP

Pa_{CO_2}		pH	HCO_3^-
100	≈	7.10	30
80	≈	7.20	28
60	≈	7.30	26
40	≈	7.40	24
30	≈	7.50	22
20	≈	7.60	20
10	≈	7.70	18

EX: ACUTE CHANGES ON CVF

AVF on CVF		CVF Baseline		AAH on CVF
		pH		
7.21	←	7.39	→	7.53
		Pa_{CO_2}		
110	←	76	→	51
		HCO_3		
43	←	41	→	37
		Pa_{O_2}		
34	←	61	→	46

CVF: Chronic ventilatory failure
AVF: Acute ventilatory failure
AAH: Acute alveolar hyperventilation

Pa_{O_2} AND Sa_{O_2} RELATIONSHIP

	Pa_{O_2}	Sa_{O_2}
Normal	97	97
Range	>80–100	>95
Hypoxemia	<80	<95
Mild	60–80	90–95
Moderate	40–60	75–90
Severe	<40	<75

Pa_{O_2} AND Sa_{O_2} RELATIONSHIP

P_{O_2} 30 ≈ 60% saturated
P_{O_2} 40 ≈ 75% saturated
P_{O_2} 50 ≈ 85% saturated
P_{O_2} 60 ≈ 90% saturated

FI_{O_2} AND Pa_{O_2} RELATIONSHIP

FI_{O_2}		Pa_{O_2}
0.30	≈	150
0.40	≈	200
0.50	≈	250
0.80	≈	400
1.00	≈	500

O_2 TRANSPORT

	Normal Values
D_{O_2}	1000 ml O_2/min
$\dot{V}_{O_2}$	250 ml O_2/min
$C(a-\bar{v})O_2$	5 vol%
O_2ER	25%
$S\bar{v}_{O_2}$	75%

APPENDIX VII

Calculating Heart Rate by Counting the Number of Large ECG Squares

Distance between Two QRS Complexes (no. of large squares)	Estimated Heart Rate (per minute)
1	300
1½	200
2	150
2½	125
3	100
3½	85
4	75
4½	65
5	60
5½	55
6	50
6½	45

APPENDIX VIII

Answers to Review Questions in Text

The Anatomy and Physiology of the Respiratory System

CHAPTER 1

1. A
2. D
3. A
4. B
5. A
6. D
7. A
8. D
9. D
10. B
11. C
12. C
13. C
14. A
15. D
16. A
17. B
18. C
19. B
20. A

Ventilation

CHAPTER 2

1. A
2. A
3. D
4. D
5. C
6. C
7. B
8. B
9. D
10. B
11. A
12. D
13. D
14. 6375 mL
15. Part I: 79 mL/cm H_2O
    Part II: 70 mL/cm H_2O
    Part III: decreasing
16. D
17. C
18. A
19. D
20. A

Clinical Application Questions

CASE 1

1. Caved inward
2. Partially collapsed; decreased
3. Positive pressure; moved outward; resting level

CASE 2

1. Low
2. Large; little or no
3. Tracheobronchial tree constriction; excessive airway secretions
4. Longer; long
5. Decreases

Pulmonary Function Measurements

CHAPTER 3

1. D
2. B
3. D
4. D
5. C
6. B
7. D
8. B
9. B
10. B
11. A

Clinical Application Questions

CASE 1

1. Personal best PEFR
2. Effort-independent flow; dynamic compression; equal pressure point
3. Closer to the alveoli

CASE 2

1. FVC; FEV_1; $FEF_{200-1200}$; PEFR
2. VC; RV; FRC
3. Increased; increased

The Diffusion of Pulmonary Gases

CHAPTER 4

1. C
2. C
3. A
4. D
5. B
6. C
7. C
8. D
9. A
10. B

Clinical Application Questions

CASE 1

1. Also increase
2. Decreased
3. PA_{O_2}; P_1
4. Pressure at the level of the alveoli; FI_{O_2} to 0.4

CASE 2

1. Thickness
2. Pa (P_1)
3. T (thickness)
4. Increased oxygen concentration (P_1)

The Anatomy and Physiology of the Circulatory System

CHAPTER 5

1. D
2. C
3. B
4. C
5. A
6. D
7. B
8. B
9. B
10. A
11. B
12. D
13. D
14. D
15. A

Clinical Application Questions

CASE 1

1. Baroreceptors; decreased
2. Blood pressure (78/42 mm Hg)
3. Decreases
4. (1) Lowering the patient's head and elevating her legs, which used the effects of gravity to move blood to the patient's lungs; (2) replacing the volume of blood lost by administering Ringer's lactated solution through the patient's intravenous tube

CASE 2

1. High blood pressure of 214/106 mm Hg
2. Course crackles
3. Decreased Pa_{O_2} of 48 mm Hg
4. Distended neck veins and peripheral edema
5. Afterloads

Oxygen and Carbon Dioxide Transport

CHAPTER 6

1. A
2. C
3. C
4. B
5. B
6. D
7. D
8. C
9. D
10. D

11. Case Study: Automobile Collision Victim

Based on the questions asked and the information provided, the patient's PA_{O_2}, Cc_{O_2}, and $C\bar{v}_{O_2}$ should first be calculated.

$$
\begin{aligned}
PA_{O_2} &= (BP - PH_2O)\, FI_{O_2} - Pa_{CO_2}\,(1.25)\\
&= (745 - 47)\, 0.50 - 38\,(1.25)\\
&= (698)\, 0.50 - 47.5\\
&= 349 - 47.5
\end{aligned}
$$

Answer = 301.5 mm Hg

$$
\begin{aligned}
Cc_{O_2} &= (Hb \times 1.34) + PA_{O_2} \times 0.003\\
&= (11 \times 1.34) + 301.5 \times 0.003\\
&= 14.74 + 0.904
\end{aligned}
$$

Answer $= 15.64 \text{ mL/dL } O_2$

$$\begin{aligned} Ca_{O_2} &= (Hb \times 1.34 \times Sa_{O_2}) + (Pa_{O_2} \times 0.003)\\ &= (11 \times 1.34 \times 0.90) + (60 \times 0.003)\\ &= 13.266 + 0.18 \end{aligned}$$

Answer $= 13.446 \text{ mL/dL } O_2$

$$\begin{aligned} C\bar{v}_{O_2} &= (Hb \times 1.34 \times S\bar{v}_{O_2}) + (P\bar{v}_{O_2} \times 0.003)\\ &= (11 \times 1.34 \times 0.65)\ 1\ (35 \times 0.003)\\ &= 9.581 + 0.105 \end{aligned}$$

Answer $= 9.686 \text{ mL/dL } O_2$

With the above information and the data provided in the question, the following can now be calculated:

A. Total oxygen Delivery

$$\begin{aligned} \text{Total oxygen Delivery} &= \dot{Q}_T \times Ca_{O_2} \times 10\\ &= 6 \text{ L} \times 13.446 \text{ mL/dL} \times 10\\ &= 806.76 \text{ mL } O_{2/\text{min}} \end{aligned}$$

Answer: $806.76 \text{ mL } O_2\text{/min}$

B. Arterial-venous oxygen content difference $C(a - \bar{v})_{O_2}$

$$\begin{aligned} C(a - \bar{v})_{O_2} &= Ca_{O_2} - C\bar{v}_{o}\\ &= 13.446 - 9.686\\ &= 3.760 \text{ mL/dL } O_2 \end{aligned}$$

Answer: $3.76 \text{ mL/dL } O_2$

C. Intrapulmonary shunting $(\dot{Q}_S/\dot{Q}_T)$

$$\begin{aligned} (\dot{Q}_S/\dot{Q}_T) &= \frac{Cc_{O_2} - Ca_{O_2}}{Cc_{O_2} - C\bar{v}_{O_2}}\\ &= \frac{15.644 - 13.446}{15.664 - 9.686}\\ &= \frac{2.198}{5.958}\\ &= 0.368\% \end{aligned}$$

Answer: 36.8%

D. Oxygen consumption $(\dot{V}_{O_2})$

$$\begin{aligned} \dot{V}_{O_2} &= \dot{Q}_T[C(a - \bar{v})_{O_2} \times 10]\\ &= 6\text{L} \times 3.760 \times 10\\ &= 225.6 \text{ mL } O_2\text{/min} \end{aligned}$$

Answer: $225.6 \text{ mL } O_2\text{/min}$

E. Oxygen extraction ratio

$$\begin{aligned} \text{Oxygen extraction ratio} &= \frac{Ca_{O_2} - C\bar{v}_{O_2}}{Ca_{O_2}}\\ &= \frac{13.446 - 9.686}{13.446}\\ &= \frac{3.760}{13.446}\\ &= 0.279 \end{aligned}$$

Answer: 27.9%

Clinical Application Questions

CASE 1

1. Unconscious, cyanotic, and hypotensive, and her skin was cool and damp to the touch
2. D_{O_2}, O_2ER
3. 68%

CASE 2

1. Decreased; increased
2. Increased; increased; decreased
3. Right
4. Lower

Acid–Base Balance and Regulation

CHAPTER 7

1. D
2. B
3. A
4. C
5. D
6. D
7. D
8. D
9. D
10. B
11. A
12. B
13. 9 mEq/L
14. Both metabolic and respiratory acidosis
15. Acute alveolar hyperventilation with partial renal compensation, or partially compensated respiratory alkalosis

Clinical Application Questions

CASE 1

1. Impaired
2. Left
3. Cherry red
4. Increased the total oxygen delivery
5. (1) Low Pa_{CO_2}; (2) loss of stomach acid
6. Decreased Pa_{CO_2}

CASE 2

1. Acids
2. Low Pa_{O_2} (38 mm Hg), which produces lactic acids
3. Aggressive ventilation
4. Higher

Ventilation-Perfusion Relationships

CHAPTER 8

1. D
2. C
3. D
4. D
5. B

Clinical Application Questions

CASE 1

1. Ineffective
2. Wasted or dead space
3. Decreased; decreased

CASE 2

1. Low
2. Fall
3. A. decreased; B. increased; C. decreased; D. increased; E. decreased

Control of Ventilation

CHAPTER 9

1. C
2. B
3. D
4. A
5. D
6. D
7. D
8. C
9. D
10. B

Clinical Application Questions

CASE 1

1. True
2. False
3. Peripheral chemoreceptors
4. Decreases
5. An increased Pa_{CO_2} level, the formation of H^+, and the stimulation of the central chemoreceptors, which, in turn, increases the individual's ventilatory rate

CASE 2

1. Ketone acids
2. Peripheral chemoreceptors
3. No
4. The decreased Pa_{CO_2} worked to offset the patient's acidic pH level caused by the increased ketone acids.

Fetal Development and the Cardiopulmonary System

CHAPTER 10

1. B
2. B
3. A
4. D
5. A
6. B
7. D
8. D
9. D
10. D

Clinical Application Questions

CASE 1

1. 28th
2. Respiratory distress syndrome (RDS)
3. Interstitial edema; intra-alveolar edema; intra-alveolar hemorrhage; alveolar consolidation; intra-alveolar hyaline membrane formation; atelectasis
4. All the conditions listed in answer 3 cause the alveolar-capillary membrane's thickness to increase.
5. Cyanosis, increased respiratory rate and heart rate, and decreased Pa_{O_2}; nasal flaring, intercostal retractions, exhalation grunting, bilateral crackles, and ground-glass appearance and air bronchogram on the chest X-ray

6. Because the baby's Pa_{O_2} was less than 45 mm Hg shortly after he was born, the ductus arteriosus remained patent. As the infant's Pa_{O_2} increased, the ductus arteriosus closed and the signs and symptoms associated with PPHN disappeared.

CASE 2

1. The ability of the fetus to absorb oxygen, nutrients, and other substances and excrete carbon dioxide and other wastes was interrupted. Complete separation brings about immediate death of the fetus.
2. Abdominal pain, uterine tenderness, uterine contraction, and hemorrhage
3. Shock and death can occur in minutes; cesarean section

Aging and the Cardiopulmonary System

CHAPTER 11

1. D
2. D
3. D
4. B
5. D
6. C
7. D
8. D
9. D
10. C

Electrophysiology of the Heart

CHAPTER 12

1. A
2. C
3. C
4. A
5. B
6. B
7. D
8. A
9. B
10. D

The Standard 12-ECG Lead System

CHAPTER 13

1. D
2. A
3. D
4. D
5. B
6. B
7. C
8. C
9. A
10. D

ECG Interpretation

CHAPTER 14

1. QRS duration: *0.06 second,* QT duration: *0.40 second*

   Ventricular rate and rhythm: *86/min*

   Atrial rate and rhythm: *86/min*

   PR interval: *0.16 second*

   Interpretation: *sinus rhythm 86/min with one PAC (6th complex)*

2. QRS duration: *0.08 second,* QT duration: *cannot determine*

   Ventricular rate and rhythm: *75–150/min*

   Atrial rate and rhythm: *cannot determine*

   PR interval: *none*

   Interpretation: *atrial fibrillation, ventricular rate 75–150/min*

3. QRS duration: *0.10 second,* QT duration: *0.44 second*

   Ventricular rate and rhythm: *50/min regular*

   Atrial rate and rhythm: *50/min regular*

   PR interval: *0.16–0.20 second*

   Interpretation: *sinus bradycardia at 40/min*

4. QRS duration: *0.40–0.10 second*

   QT duration: *cannot determine*

   Ventricular rate and rhythm: *86–100/min*

   Atrial rate and rhythm: *300*

   PR interval: *none*

   Interpretation: *atrial flutter, ventricular rate 86–100/min*

5. QRS duration: *0.08 second,* QT duration: *0.36 second*

   Ventricular rate and rhythm: *86/min*

   Atrial rate and rhythm: *75/min*

   PR interval: *0.24 second*

   Interpretation: *first-degree AV block*

6. QRS duration: *0.12 second,* QT duration: *0.32 second*

   Ventricular rate and rhythm: *168/min regular*

   Atrial rate and rhythm: *cannot determine*

   PR interval: *cannot determine*

   Interpretation: *ventricular tachycardia at 168/min*

7. QRS duration: *0.08 second,* QT duration: *0.28 second*

   Ventricular rate and rhythm: *150/min regular*

   Atrial rate and rhythm: *150/min regular*

   PR interval: *0.16 second*

   Interpretation: *sinus tachycardia at 150/min*

8. QRS duration: *cannot determine*

   QT duration: *cannot determine*

   Ventricular rate and rhythm: *cannot determine*

   Atrial rate and rhythm: *cannot determine*

   PR interval: *cannot determine*

   Interpretation: *ventricular fibrillation*

9. QRS duration: *0.08 second,* QT duration: *0.38 second*

   Ventricular rate and rhythm: *60/min*

   Atrial rate and rhythm: *60/min*

   PR interval: *0.16 second*

   Interpretation: *sinus ventricular rate at 60/min with a PAC (last complex)*

10. QRS duration: *0.06 second,* QT duration: *0.32 second*

    Ventricular rate and rhythm: *125/regular*

    Atrial rate and rhythm: *125/regular*

    PR interval: *0.16 second*

    Interpretation: *sinus tachycardia at 125/min with frequent uniform PVCs*

Hemodynamic Measurements

CHAPTER 15

1. F
2. E
3. A
4. K
5. D
6. G
7. J
8. B
9. D
10. I
11. D
12. D
13. D
14. D
15. A

Clinical Application Questions

CASE 1

1. The SVR (peripheral vascular resistance) to increase
2. Nitroprusside is a vasodilator. It was used to reduce the patient's afterload.
3. As the patient's SVR decreased in response to the nitroprusside, the left ventricular afterload also decreased. This action in turn allowed blood to be more readily ejected from the left ventricle.

CASE 2

1. 5 cm H_2O was the PEEP level that produced the least depression of cardiac output and the maximum total oxygen delivery.
2. Profile 1:

$$\begin{aligned} Ca_{O_2} &= (Hb \times 1.34 \times Sa_{O_2}) + (Pa_{O_2} \times 0.003) \\ &= (15 \times 1.35 \times 0.91) + (57 \times 0.003) \\ &= (20.1 \times 0.91) = 0.17 \\ &= 18.29 + 0.17 \\ &= 18.46 \end{aligned}$$

Profile 2:

$$\begin{aligned} Ca_{O_2} &= (Hb \times 1.34 \times Sa_{O_2}) + (Pa_{O_2} \times 0.003) \\ &= (15 \times 1.35 \times 0.9) + (61 \times 0.003) \\ &= (20.1 \times 0.91) = 0.18 \\ &= 18.09 + 0.18 \\ &= 18.27 \end{aligned}$$

Profile 1:

$$\begin{aligned} D_{O_2} &= \dot{Q}_T \times (Ca_{O_2} \times 10) \\ &= 3.83 \times (18.46 \times 10) \\ &= 3.83 \times 184.6 \\ &= 707 \text{ mL } O_2/\text{min} \end{aligned}$$

Profile 2:

$$\begin{aligned} D_{O_2} &= \dot{Q}_T \times (Ca_{O_2} \times 10) \\ &= 3.1 \times (18.27 \times 10) \\ &= 3.1 \times 182.7 \\ &= 566 \text{ mL } O_2/\text{min} \end{aligned}$$

A PEEP of 5 cm H_2O resulted in a D_{O_2} of 707 mL O_2/min. A PEEP of 10 cm H_2O resulted in a D_{O_2} of 566 mL O_2/min. The "best PEEP" in this case was 5 cm H_2O, which resulted in a D_{O_2} that was 141 mL O_2/min more than the PEEP of 10 cm H_2O.

Renal Failure and Its Effects on the Cardiopulmonary System

CHAPTER 16

1. D
2. B
3. B
4. D
5. C
6. D
7. D
8. B
9. B
10. D

Clinical Application Questions

CASE 1

1. The patient's left ventricular failure (a prerenal abnormality)
2. A sharp reduction in urine output
3. Because of increased H^+ and K^+ ion levels and the loss of HCO_3^-
4. Fluid accumulation in the patient's lungs and extremities, causing swelling in the patient's ankles, hands, and eyelids; white fluffy patches visible on the patient's chest X-ray; Pa_{O_2} of 64 mm Hg

CASE 2

1. Hypovolemia
2. Inflammation of the tracheobronchial tree, bronchospasm, excessive bronchial secretions and mucous plugging, decreased mucosal ciliary transport mechanism, atelectasis, alveolar edema, and frothy secretions
3. White fluffy densities throughout both fields (X-ray), and the low Pa_{O_2} of 47 mm Hg

Sleep Physiology and Its Relationship to the Cardiopulmonary System

CHAPTER 17

1. E
2. C
3. B
4. D
5. A
6. B
7. B
8. B
9. A
10. A

MATCHING

1. D
2. E
3. A
4. B
5. C

Clinical Application Questions

CASE 1

1. 10, 10
2. True
3. True

Exercise and Its Effects on the Cardiopulmonary System

CHAPTER 18

1. B
2. D
3. D
4. D
5. C
6. B
7. D
8. D
9. A
10. D

High Altitude and Its Effects on the Cardiopulmonary System

CHAPTER 19

1. D
2. D
3. D
4. B
5. D
6. True
7. False
8. True
9. True
10. False

High-Pressure Environments and Their Effects on the Cardiopulmonary System

CHAPTER 20

1. C
2. B
3. D
4. D
5. D
6. True
7. True
8. False
9. True
10. True

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